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ABSTRACT

A teacher uses reflections, analysis, and study of her own teaching and learning across a 23-year period to consider a case of science knowledge development. Because her learning about science has become increasingly influenced by analyses of her own students learning, the teacher's pedagogical autobiography is interwoven with stories of her students' changing understandings of science, focusing particularly on a case study of one student's learning about science across a year. The report concludes with a discussion of implications of the autobiographical journey. Conditions that supported the teacher's growth are used to consider ways of supporting prospective and practicing teachers' education and development in two areas: development across time of increasingly complex and rich knowledge about what it means to understand science and development of an inquiring, reflective, and analytical stance towards learning from science. (Author/PR)

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Kathleen J. Roth

Center for the
Learning and Teaching
of Elementary Subjects

Institute for
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College of Education

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Abstract

What kinds of understandings of science are needed in science teaching, and what conditions and dispositions can enable that knowledge to develop across a teaching career? How can learners' understandings and struggles in science contribute to a teacher's science knowledge growth? In this report, an autobiographical approach is used to explore these questions. The author uses reflections, analysis, and study of her own teaching and learning across a 23-year period to consider a case of science knowledge development. Because her learning about science has become increasingly influenced by analyses of her students' learning, the author's pedagogical autobiography is interwoven with stories of her students' changing understandings of science, focusing particularly on a case study of one student's learning about science across a school year.

The autobiographical case study highlights how the author's learning about what it means to understand science has been closely intertwined with her learning about how to study and learn from teaching. The report illustrates how these two strands of learning--about science and about learning from teaching--developed over time, emphasizing the kinds of supports that enabled this growth.

The report concludes with a discussion of implications of this autobiographical journey. Conditions that supported the author's growth are used to consider ways of supporting prospective and practicing teachers' education and development in two areas: development across time of increasingly complex and rich knowledge about what it means to understand science and development of an inquiring, reflective, and analytical stance towards learning from teaching.

In addition to generating some implications for teacher education and development, this case study of one teacher and her students' learning about science across time could be useful to prospective and practicing teachers for study purposes. For example, the report could be helpful to prospective teachers who are trying to define the kinds of knowledge they will need to teach science effectively. The report could support them in considering aspects of scientific knowledge that they need to develop while also giving them ideas about ways to approach that learning beyond their formal study in college. Practicing teachers and administrators may find the case study useful in thinking about restructuring schools and teachers' roles to enable a qualitatively different kind of professional learning than the learning that is traditionally accomplished through inservice workshops--a learning that includes ongoing in-depth examination of what it means to know the subject (science in this case). College educators, both in teacher education and in the sciences, may find the case useful in reexamining approaches to science preparation for intending teachers. Finally, it is the author's hope that this opening up of her practice and learning to the professional community will encourage others to do the same so that the lessons learned from this case can be enriched, challenged, and reexamined through others' autobiographies and experience.

WHAT DOES IT MEAN TO UNDERSTAND SCIENCE?: CHANGING PERSPECTIVES FROM A TEACHER AND HER STUDENTS

Kathleen J. Roth[1]

Introduction: An Autobiographical Approach

What kinds of understandings of science are needed for science teaching? This is a question that is often explored using survey data about the kinds and numbers of science courses that science teachers have taken. This data is then matched to self reports of teachers' comfort in teaching science as well as to studies of science teacher effectiveness (Fulton, Gates, & Krockover, 1980; Horn & James, 1981; Weiss, 1978; Weiss, 1987). Other researchers study the question in the context of classroom studies of teaching and learning (Hollon, Roth, & Anderson, 1991; Roth, 1987). In a study of middle school science teachers, for example, my colleagues and I conducted in-depth interviews with teachers that probed their knowledge of science, of particular science concepts they were teaching, and of science teaching and learning. We then observed them teaching several units of instruction and studied their students' learning. Such studies enabled us to look closely at the interactions among teachers' knowledge of science, their teaching of science, and students' learning. These studies provided snapshots of teachers' knowledge and understandings at a given point in time. If we view teacher learning as a lifelong process, however, these studies do not provide a moving picture of how a teacher's understandings of science might change and grow across a teaching career. Nor do they help us understand the kinds of conditions that would support meaningful teacher learning about science as part of teacher development.

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To begin to explore this aspect of teacher learning across time, I took a different approach to understanding the interactions among a teacher's understanding of science, her teaching, and students' learning. Again, I explored teacher knowledge in the context of a case of science teaching and learning. But in this case, I am both the teacher and the researcher--taking on a new role for teachers in which teaching is defined as including systematic reflection, analysis, and the construction and sharing of knowledge about teaching and learning. This view of teaching as research (Duckworth, 1986) enables me to construct an autobiographical approach to a consideration of important questions about teachers' knowledge in science teaching: What kinds of science knowledge do science teachers need? What conditions and dispositions can enable that knowledge to develop across a teaching career? How can learners' understandings and struggles in science contribute to a teacher's science knowledge growth? In this report, I focus on my own science teaching and use that to consider how my own knowledge for science teaching has developed in response to the demands of that teaching. My autobiography is influenced by the learning and struggles of my students. For that reason, this autobiographical analysis of my own developing understandings of science is interwoven with stories of my students' changing understandings of science, focusing particularly on a case study of one student's learning about science across a school year.

The autobiography highlights two kinds of learning that have grown and developed across my career--my learning about what it means to understand science and my learning about how to learn from teaching. I see these two learning strands as closely intertwined, for my learning about science would have stopped early in my career if I had not learned to take a new view of professional learning through inquiry into my own practice. The report will illustrate how these two strands of my learning developed over time, emphasizing the kinds of supports that enabled this growth.

This autobiography represents a case study of one teacher's learning about science. Of what use is such an autobiographical tale to others? How can a reflection and analysis of my learning as a teacher contribute to our professional knowledge and practice? There have been many times of apprehension as I wrote this report, wondering about the answer to this question. It is my hope that my experiences will be helpful to prospective teachers who are trying to define the kinds of knowledge they will need to teach science effectively. The report could support them in considering aspects of scientific knowledge that they wish to develop while also giving them ideas about ways to approach that learning beyond their formal study in college. Practicing teachers and administrators may find my experiences useful in thinking about restructuring schools and teachers' roles to enable a qualitatively different kind of professional learning than the learning that is traditionally accomplished through inservice workshops--a learning that includes ongoing in-depth examination of what it means to know the subject (science in this case). College educators, both in teacher education and in the sciences, may find my experiences useful in reexamining approaches to science preparation for intending teachers. Finally, I hope that this opening up of my practice and learning to the professional community will encourage others to do the same so that the lessons learned from my case can be enriched, challenged, and reexamined through others' autobiographies and experiences.

The report is divided into five sections. As an introduction, I describe the view of scientific understanding that I used in teaching a group of fifth graders during 1988-89. A central goal of my science teaching was to help these students construct important and personally meaningful scientific understandings of the world around them. I describe a midyear interview with one of my fifth grade students, Kelly, (names of students and teachers are pseudonyms) to illustrate the kinds of scientific understanding that I was seeking and to compare my goals as a teacher with scientists' ways of knowing. In the second section I look backward in time and consider how the framework for thinking about scientific understanding that guided my teaching of Kelly developed across my professional career. In this pedagogical autobiography I emphasize how my own understanding of science changed and developed as a result of a variety of teaching and other professional activities. In section three I trace one of my fifth-grade student's understanding of science as it developed across the 1988-89 school year. This analysis of Brenda and her changing understandings of science and my new teacher-researcher role shaped my continuing learning about what it means to understand science and to learn about science from teaching. In the fourth section I look forward from my teaching of Brenda, showing how my study of her learning challenged my ways of understanding and representing science in my teaching. This section highlights the role that researchers and other educators observing in my classroom play in shaping my views of what it means to understand science. Finally, I consider in section five the implications of this autobiographical journey: What are the conditions and dispositions that supported (and continue to support) my science knowledge growth? What are the implications of this autobiographical analysis for science teacher education and development?

Part 1: Comparing Scientists' Ways Of Knowing With A Fifth Grader's Way Of Knowing Science: My Views of Meaningful Scientific Understanding in 1988-89

Over the last several years I have been teaching science and social studies to fifth graders in two public schools near my university. One school is an urban school with a student population of approximately 20% minority (primarily African American). The community is predominantly working and middle class, with only a few college-educated parents. The other school is located in a blue collar suburb of this city; students here also come primarily from working class families but the population is primarily Caucasian. This school serves a low income trailer park nearby and is considered to have the highest percentage of "at-risk" students of the five elementary schools in the district.

In these classrooms I am trying, like all science teachers, to help students understand science. But what does it mean to "understand" science, and what do I count as understanding in my students? I would like to start the autobiography of my learning about science by describing the features of scientific understanding that served as a framework for my teaching in 1988-89. To illustrate these features, I will compare selected aspects of scientists' ways of knowing science with my goals for my fifth graders' understanding. Excerpts from a midyear interview with one of my fifth grade students, Kelly, will provide examples of what I was counting as "understanding" in 1988-89. Thus, Kelly (a cooperative, attentive student who was very strong in math while struggling in reading with a label as learning disabled) represents a student who developed the kinds of scientific knowledge that I associated with scientific understanding. Obviously, the students I teach know far less about the topics they study than adult scientists do, so on what basis can I claim that they "understand?" Drawing from analyses of both philosophy of science and of children's experiences in science classrooms, my colleague, Charles Anderson, and I identified several aspects of scientific knowledge that seem to be more or less universal characteristics of meaningful scientific understanding. These features of scientific understanding guided my teaching of Kelly and her classmates. Meaningful science knowledge, for both the scientist and the school science student (see Figure 1):

a. Is connected, well-structured

b. Is useful in describing, predicting, explaining, designing, and appreciating real-world, natural phenomena

c. Is constantly changing, building, deepening over time

d. Is shared by a community that cooperatively constructs new knowledge and understanding.

These ways of thinking about what it means to understand science contrast sharply with the ideas I held as a beginning teacher. After my description of my thinking about these features as I taught Kelly, I will travel first back in time to trace how these ways of thinking about scientific understanding developed across my professional career. Later I will examine in depth how a case study of another student in this class, Brenda, propelled my learning and growth about science forward. I hope to show how my study of Kelly and Brenda helped me see ways in which this structure for thinking about scientific understanding was both powerful and limited.

Features of Scientists' Understandings: My 1988-89 Perspective

The knowledge held by adult scientists exhibits each of the above characteristics of understanding. Indeed, our society values their knowledge and supports the scientific enterprise because their knowledge has those characteristics. Each characteristic is explained and illustrated below.

Connections and structure. When I say that scientific knowledge is "connected" or "well structured," I do not mean to imply that it has the sort of static structure that we associate with buildings, or the organization of books in a library, or even the organization of data in a computer. Instead, I would like to use the word "structure" in something like the way that biologists use that term. The structures of scientific knowledge, like biological structures, are dynamic and constantly changing. Systems of scientific knowledge are also like biological systems in that multiple structures or patterns exist within any given topic of discipline. Thus it is difficult to discuss "the" structure of scientific knowledge not because it lacks structure, but because it is highly structured in so many different ways.

Toulmin (1972) uses the metaphor of an "intellectual ecology" to explain the structure of a scientific discipline. Any concept, like an individual organism in an ecosystem, is associated with many other concepts (organisms and environment) in a variety of ways and depends for its "life" or meaning on those associations. Adult scientists have developed large systems of richly interconnected ideas and depend on them to do their work.

Usefulness. Adult scientists use their knowledge for a variety of purposes that are both socially important and personally rewarding. Among those purposes are description, explanation, prediction, design, and appreciation of real-world systems or events. Each of these uses of scientific knowledge is described briefly below.

1. Description. Scientists often use their knowledge for purposes that are essentially descriptive in nature: Providing names for things, measuring them, classifying them, describing them. One reason that scientific knowledge is valued so widely is that it

Meaningful Science Knowledge

- Is connected, well structured
- Is useful in describing, predicting, explaining, controlling, appreciating, real-world, natural phenomena.
- Is constantly changing, building, deepening over time
- Is shared by a community that cooperatively constructs new knowledge and understanding
- Raises questions for further exploration

Figure 1. My views of important aspects of scientific understanding in 1988-89.

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gives us the ability to provide precise and accurate names, descriptions, or measurements of natural systems or phenomena.

2. Explanation. Explanation is a primary goal of science. We acquire scientific knowledge and develop theories to explain how the natural world works; Einstein once called scientists people "with a passion to explain." Thus, a scientist uses and constructs knowledge in trying to explain how natural systems work, why various phenomena occur, or why the world is as it is.

3. Prediction. The ability to generate accurate predictions is a key test of the validity of a scientific theory as well as an important use of scientific knowledge. Scientifically literate adults often use their scientific knowledge to generate predictions about future observations or events.

4. Design. We also value scientific knowledge because we use it to design technologies that give us partial control over natural systems and events. Technological applications of scientific knowledge often have great social, political, and economic importance and power.

5. Appreciation. Finally, scientists are often attracted to their fields as much for personal, aesthetic reasons as for utilitarian reasons. Their scientific knowledge gives them a richness and depth of understanding that helps them to appreciate the wonders, beauties, complexities, and puzzles of the world around them.

Change and development. No matter how useful the knowledge that it has produced, a scientific field that is no longer changing and developing is characterized as "stagnant" and declines in power and importance. Like living organisms, scientific fields are inherently dynamic; the only alternative to growth is decay.

The same can be said of the knowledge of individual scientists. An important part of what scientists know is how to learn more, how to ask and pursue new questions that have the potential to produce significant new insights. By virtue of both selection and training scientists generally have a disposition to inquire, to try to make sense of what they do not yet understand, and to demand more satisfying and complete explanations of the world. For successful scientists, this disposition to inquire is supported by a wide array of skills and strategies that they use to push the limits of their knowledge.

One consequence of this disposition to inquire is that scientists must become accustomed to living in a more or less constant state of uncertainty. Rather than avoiding situations that are confusing or puzzling, scientists seek them out and try to fit the pieces together. When the important ambiguities or uncertainties about a problem have been resolved, scientists lose interest and move on to other problems about which they are still uncertain.

Sharing by a community. Finally, scientific knowledge is a social rather than an individual phenomenon. Each individual scientist is a member of a professional community that is engaged in a collective attempt to understand the natural world. Scientists can contribute to the development of knowledge in their fields only through participation in their professional communities. New knowledge is considered valid only after it has been reviewed and accepted by the community, and scientists are expected to participate in discussions and debates within the community. No individual scientist knows all that is know about a topic; the growing body of scientific knowledge is the product, and the possession, of the community as a whole.

Students' Scientific Understandings: The Case of Kelly

When I say that I am trying to teach for understanding in my science classes, I obviously do not mean that I am trying to get my students to understand everything that scientists understand; that is obviously impossible. Instead, I mean that I would like my students to develop knowledge that, while limited, has the characteristics described above: coherence and structure, usefulness, change and development, and sharing by a community.

In my 1988-89 fifth-grade science teaching, I was particularly interested in supporting and analyzing the students' developing understandings of scientific concepts over time: How successful are students in developing meaningful understandings of concepts? Which ideas/concepts make sense to students in increasingly complex ways across the school year? To answer these questions I kept copies of all written work completed by students, audiotaped and/or videotaped lessons to analyze participation patterns and responses to instruction, and conducted periodic interviews with students about their learning.

To illustrate the features of scientific understanding that I hoped my students would develop, I draw from a midyear interview with Kelly. The interview focused primarily on a recent unit studied in science about the human body and cell respiration. The unit explored how the digestive, respiratory, and circulatory systems interact to help all body cells get food and oxygen (for cell respiration). Central questions serving as the framework for these studies were: What happens to food after you eat it? What happens to air after you breathe it in? Students were to develop the understanding that both food and oxygen are needed by each body cell: The oxygen combines with the food to release the energy which the cell can then use for growth and life processes. The interview also included two questions about a unit studied earlier in the year about plants and photosynthesis.

Connectedness of Kelly's science knowledge. In responding to both interview and test questions , Kelly demonstrated that her knowledge about both the human body and about plants was what I would consider to be well-organized, connected knowledge. The first question asked Kelly to describe what she had been studying in science. Without hesitation, Kelly picked out the major ideas of the unit: "We've been studying about the different body systems--the digestive system, the respiratory system and a little bit about the nervous system. We've been talking about why we need oxygen and food to live--so our cells can make more cells, to grow, and for some cells to move around, like red blood cells move around." Without prompting, she added, "Before that we were studying about plants--how they make their food and what they need." Kelly is not just naming off little bits of information randomly or summarizing the topics studied (the human body, plants); instead, she is able to talk about the big ideas that had been developed.

When asked to incorporate more details and concepts into this picture, Kelly was easily able to elaborate on the framework she had given. On one question, for example, she was given 16 concept cards to arrange in some way that made sense to her. Kelly quickly arranged the cards (see Figure 2). She explained:

> Food is energy and the energy, or the food, goes into the digestive system, into the small intestines where it gets mushed up a little more, and then to the blood vessels and then to all the cells of the body. The circulatory system, well, the food and energy goes there after it's digested. The respiratory system, the oxygen goes in through the trachea to the lungs, then to the air sacs and into the blood vessels and to the cells. (Kelly added trachea and air sacs to the list of cards).

On her test and in class, Kelly demonstrated that she could add many more detailed facts to this picture--she knew, for example, the names of many parts of the digestive system (salivary glands, esophagus, stomach, small intestine, villi, semipermeable intestine wall, large intestine, rectum, anus) and could even talk about the pancreas and the liver and the gall bladder as making and delivering digestive juices to the small intestine to help with the digestive process. But these facts were organized into a framework of body systems working together to get food and oxygen to the body cells. Kelly did not describe these facts about body parts as being what the unit was all about.

It was particularly interesting how Kelly connected this knowledge about the human body systems with her knowledge about plants. The interviewer asked her if a plant sitting on the table had anything to do with what she had studied about concerning the human body systems. Again, almost without a hesitation, Kelly responded that yes, they were similar in certain ways: "The plant gets its food by making it and then the food goes to every part of its body. And that's like our food goes to all our cells." Since this connection between plants and people had not been discussed in class at the point of this interview, it is striking that Kelly remembered key issues that had been discussed about

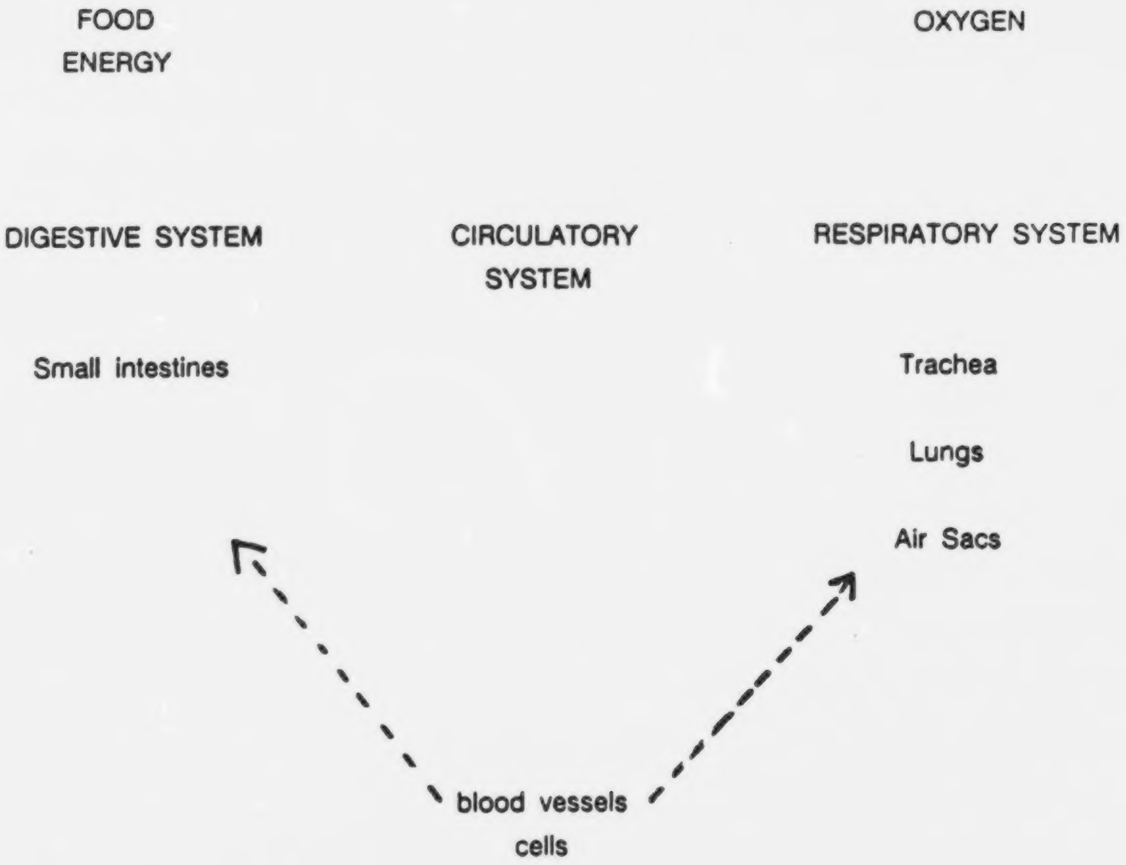
FOOD
ENERGY
OXYGEN
DIGESTIVE SYSTEM
CIRCULATORY SYSTEM
RESPIRATORY SYSTEM
Small intestines
Trachea
Lungs
Air Sacs
blood vessels
cells

Figure 2. Kelly's concept map. (Dotted lines show how she moved cards as she explained them.)

plants almost two months earlier and that she was also able to use those ideas and link them in a comparison with people.

Usefulness of Kelly's knowledge. Kelly described the knowledge about the human body as useful both as a way to satisfy one's curiosity ("Your kids will want to know why you need it and where it goes, and you can tell them") and as a source of information that might help keep you healthy ("If you try to hold your breath, you might have cells die and get sick and you wouldn't know why"). She talked about how she had never known before why you need oxygen or that food went all over the body. These ideas were useful to her in explaining novel situations posed to her during the interview. For example, she explained how cough syrup might work ("It goes into the digestive system and then the blood cells takes it all over the body. When it gets to the lungs, it will help cure the lungs. It will go into the cells in the lungs and take the bacteria out.") and how drinking alcohol might be harmful to a developing fetus in a pregnant woman: "She drinks it [alcohol] and it goes down her esophagus into her stomach and then it goes into the small intestines and goes into her blood vessels and the blood vessels can take the alcohol through the cord that is attached to the baby."

That her knowledge about photosynthesis had also been useful to her was revealed in this midyear interview. In talking about how a plant might be similar or different from the human body, Kelly started talking about important ideas about plants. In this description she volunteered that the carrot in a carrot plant contained stored food that was originally made by water, air, and sun "combining somehow and making food and energy that goes all over the plant." Clearly, her knowledge about photosynthesis was useful to her in explaining how common vegetables grow.

Kelly's changing and deepening understandings. Kelly was easily able to describe changes in her understanding of both the respiratory system and the digestive system.

> I didn't know before why we needed air and about oxygen and where it went. I thought it just went into the lungs and out. Now I know that it goes to the trachea and the air sacs and to the blood and to cells to release the energy from food. . . . I studied the digestive system before, but I didn't

> know about the semi-permeable. It's a tiny screen around the small intestines and the lungs. It's so your food can go through it, so it's not too big for the cells. I used to think the food just goes in and out. But that doesn't make any sense--why eat? It wouldn't serve any purpose.

In fact, Kelly decided that she found things most interesting to study when her ideas changed a lot. For this reason, she liked studying about plants better than studying about the human body: "I really didn't know all that about plants before. It's more fun to learn about something you don't already know about."

Kelly's understanding of knowledge as changing and raising new questions. It is also interesting to trace Kelly's changing understandings of plants and how they use air. At the beginning of the year, air was just something plants needed to stay alive. At the end of the photosynthesis unit in the fall, she changed this view of the role of air and knew that plants needed air as one necessary ingredient in the food-making process. By the end of the body systems unit, she elaborated these ideas even further: "Plants need two things from the air, carbon dioxide to help make their food, and oxygen to help cells release energy from food." She described how plants were similar to animals in their use of oxygen but very different in their use of carbon dioxide.

When asked whether any of the ideas she had been studying in science ever seemed confusing or puzzling to her, Kelly immediately identified two questions that this study had raised for her: How do blood cells move and carry oxygen, and why is blood blue but when you get a cut it comes out red?" The first question, in particular, reflects the disposition to want increasingly satisfying explanations. Before this unit, Kelly had not even thought about oxygen doing anything but going in and out of the lungs. Now, she knows more about what happens to oxygen in the body--she knows that it gets into the bloodstream and travels to cells--but she now has new questions that she wants answered about what happens to oxygen in the body.

When asked if she had learned anything in this unit that surprised her, Kelly raised another question that she is still puzzling about:

> If you breathe in oxygen and then carbon dioxide comes out, I'm wondering how fast can it take to go down to the cells and back out? It seems like it comes out two seconds later, and it's got too long of a way to go--to the blood vessels and to the cells and back. How fast can it do that?

Kelly's studies had raised new questions for her, and it was clear that she was actively puzzling about these questions.

Kelly's knowledge as socially constructed. Kelly recognized that learning in science class ("at least this year") was a cooperative, shared venture. She talked about how she liked working with a partner in science class because you "get to talk over ideas. You got twice the good ideas, and it's fun to work with a friend and you get better answers." The interviewer asked her how she would describe science class to someone who had never been in a science class: "You have a lot of discussions and do a lot of other things, do a lot of experiments. It's a whole group of people just talking and doing things." In elaborating on this, Kelly emphasized the importance of people asking questions: "If we're on like a special topic, you want us to ask questions about it, you know, ask a question about something we don't know yet. That's what I mean about talking about things." Kelly's description of our science classroom matches some of the norms of interaction in scientific communities that I was hoping to make more visible to students.

Summary of Kelly's science understandings. The kinds of understandings that Kelly developed were not unusual among my fifth-grade students, but they are quite different from the kinds of understandings that students had typically developed in my science classrooms earlier in my teaching career. They are also different from the kinds of understandings of students who I have studied in research projects. In other research projects, I have both tested and interviewed upper elementary and middle school students whose understandings of these same topics and concepts remained vague, confused, distorted even after weeks of instruction. Of most concern to me is that the fragmented knowledge developed by students in my earlier classes and research studies was not genuinely useful nor inspiring to them and did not become a part of their thinking about natural phenomena. Science was a school subject that was learned to pass tests and please teachers and not to make better sense of the everyday world. In contrast, Kelly (and many of her classmates) seemed to be developing the kinds of science understandings that are personally meaningful.

I was not able to teach for the kinds of understandings that Kelly and her classmates developed when I took my last formal biology course 19 years earlier and began my teaching career. So what did I learn in those 19 years, and how has it contributed to my ability to teach science for understanding? How have my ways of understanding science changed? These are questions that I consider in the next section.

Part 2: One Teacher's Developing Knowledge Of Science: Learning From Study And Teaching

As I contrast the knowledge about science that helped me plan and teach Kelly with the knowledge I had about science when I first began teaching 19 years earlier, I am struck by how much my academic knowledge of science has been transformed over the years in ways that make it much more useful for teaching for meaningful learning. These personal transformations of science knowledge highlight three issues that help distinguish science knowledge for those who do scientific research from science knowledge for those who teach:

1. First, there are important ways in which teachers' knowledge needs to be similar to the kinds of knowledge that scientists have. Some of the most important ways of knowing science that teachers need do not get taught in undergraduate science majors; they are the kinds of thinking that students do not encounter in serious ways until they enter doctoral programs in the sciences.
2. Secondly, there are important ways in which teachers' knowledge about science needs to be different from strict disciplinary views of science.
3. Third, the knowledge of science needed for teaching is intimately linked to knowledge about children and how they learn science. We need to know about how children think about particular concepts or topics in science in order to better define the knowledge of science that teachers need.

The development of these insights about science knowledge for teachers grew hand-in-hand with my development of a new orientation to thinking about the role of teacher. As I learned to embed reflection and analysis in my teaching practice--to learn from teaching instead of about teaching--I was liberated to look honestly at my practice and to learn from it rather than to justify and defend it. This disposition to inquire into my own practice was not present in the early years of my teaching; my story illustrates how this disposition grew through my experiences in teaching, research, and study.

Science Knowledge to Prepare for Graduate Study in Science

When I graduated from college with a major in biology and related work in chemistry and earth science (unfortunately, I never took a single physics course either in high school or college), my knowledge of science in some ways met the criteria defined above for scientific understanding: I understood, in a very general sense, that scientific knowledge was connected and organized in various ways, that scientific research was useful in generating new knowledge and understandings, that science was a dynamic and human endeavor. I knew some of this from my professors who told me about these ideas and in some cases modeled their own excitement in being part of the scientific community. However, these ideas about the nature of scientific knowledge and these examples of humans doing science were apart from me, just as the lecture podium in my science classes was distant from my seat (which was usually near the back of the room). These ideas were like platitudes that I had memorized; I did not have specific examples and personal experiences to make them real.

In some ways my understandings of science at that point better suited me to go on in a specialized field of scientific research than to teach. For example, the connectedness I saw in science had to do with the complexity and quantity of scientific knowledge. I saw scientific knowledge as connected in very complicated and detailed ways--in my mind science was represented by the details and intricate relationships in the Krebs cycle rather than by the big ideas related to the Krebs cycle that Kelly had learned (how the body systems work together to get food and oxygen to the cells to release energy for life). I could have accurately described the many steps in the Krebs cycle, but I doubt that I could have given a very coherent answer to the question that Kelly so eloquently explained: What happens to the air after we breathe it in? I would have gotten so bogged down in trying to remember the details that I would have missed the important main concepts. I viewed scientific knowledge as detailed and complicated and useful to the average person only indirectly--scientists would use the knowledge to improve technology, to find cures for diseases, etc. I did not see my knowledge of science as personally useful unless I used it to continue in a research career. The only immediate personal usefulness of the knowledge was a deeper appreciation and sense of wonder about the diversity and complexity of life, and this appreciation has become an important component of the knowledge that I draw on in my teaching today.

While I saw scientific research as something important in a global sense, my own work in the laboratory in college did not help me develop better understandings of the mountains of facts, formulas, and terms that I was memorizing in my courses. My laboratory work seemed to me to be a component of science that is separate from the content, the concepts in science. And the lab work was about "scientists'" questions and answers, not my own. On only one laboratory project did I feel that my work was a genuine investigation--that I was trying to answer or explore a question without a guidebook--rather than a workbook experience. Yet even in this project, the inquiry was far from genuine; the question was not one I felt passionately about although I was somewhat curious about what caused the Mimosa plant to respond to touch. And the tools and instructor support available to me left me frustrated and feeling that I could not develop a meaningful answer to my question. I remember feeling like I was resorting to Cliff's notes when I read an article about a "real" scientist's exploration of this problem. No one helped me consider that reading this article was an honest scientific activity nor that I might have done such reading prior to planning the investigation rather than as a way to find "the right answer" to put in my paper.

Like my more routine laboratory investigations this one also turned out to focus on making the right observations, getting the right answers, making the experiment "come out right." Thus, the laboratory work left me with a view of science as divided into two discrete pieces--knowledge of details and complicated interactions that needed to be learned to pass exams on the one hand, and knowledge of research procedures and laboratory skills that required following steps carefully to get right answers (and good grades) on the other. The laboratory or "process" part of science seemed to me at the time to be useful and important to scientists but not particularly useful or important to me. I developed a narrow view of these processes as a clearly defined set of procedures that would assure a good "scientific" experiment and clear-cut results.

This well-defined, straightforward process of scientific research also seemed to me to be a rather solitary undertaking; I held an almost stereotypical view of the scientist working alone in the laboratory or the greenhouse. In my own laboratory work I learned that lab partners were there for sharing equipment, not ideas, and I felt like I was cheating when I turned to a partner or the teaching assistant for help in making the lab "come out right." Laboratory reports and papers were always constructed individually, without any collaborative work. While I did understand the importance of communicating ideas to others, my view of communication in science was more that of reporting findings, telling others about experimental results. These results would then tell other scientists about new facts that would now be added to the top of the mountain of scientific knowledge. Talking with others to better understand their ideas or to argue different interpretations of experiments was not a part of my vision of scientific discourse. And why should it be? I never once remember a class session (which were always lectures or lectures with demonstrations) or a laboratory where students were encouraged to engage in debate about ideas. Even in a science and politics course, it was information given and information learned.

And this occurred despite the fact that I was in some small classes and had opportunities to interact with professors and doctoral students in my major field of study. I had rich opportunities and resources available to me--a brand new phytotron, a primate research field area, the extensive Duke Woods which included an amazing diversity of species that were introduced to me on energetically led hikes in ecology and plant identification courses, and an oceanographic research station which we visited on two weekend excursions in two different courses. The course experiences were rich enough to keep me intrigued and learning, but there were important deficits in my learning despite all the 4.0's on the transcript.

Transforming Science Knowledge to Science Knowledge for Teaching: Lessons from Teaching

My understanding of knowledge growth in science was limited in important ways when I left college and took my first teaching job, although no one ever cautioned me that there was more I needed to learn about science to be a good science teacher. With a degree in biology from a prestigious university, my science knowledge seemed to be unquestioned. Early in my teaching career, however, my ways of understanding biology underwent an important transformation as a result of my experiences teaching from some unusual science curriculum materials. These seventh grade life science materials, Interaction of Man and the Biosphere (IMB; Abraham, Beidleman, Moore, Moores, & Utley, 1975), contrast with typical science textbooks in several important ways.

First, they are not organized as a set of distinct chapters or units that can be taught in almost any sequence. In a typical biology textbook, for example, a teacher can start with Chapter 7 about invertebrates or Chapter 9 about flowering plants or Chapter 10 about ecosystems. In IMB, big ideas and concepts are gradually developed and linked together across chapters. It would be difficult to teach Section 4 about transport of food and other materials in animals and plants before teaching Sections 1, 2, and 3, which investigate food production in plants, digestion of food in animals, and the ways in which cells are structured to permit movement of materials (food, in particular) through their membranes. The sequence of these chapters is also distinctive, because it continually weaves back and forth between plants and animals, emphasizing important similarities and differences in food-getting, cell structure and function, transport, cell respiration, regulatory mechanisms, and reproduction. This contrasts with the typical phylogenetic approach to biology texts, in which the living kingdom is studied group by group (protozoans, flowerless plants, flowering plants, invertebrates, vertebrates, humans). Later sections of IMB focus on ecological interactions, drawing from the earlier sections to create a rich sense of the interdependency of living organisms and ways in which organisms are diverse yet unified by the same basic life processes.

The IMB materials are also distinctive because of the absence of the usual "all about" descriptive narrative. The typical textbook parade of bold-faced words, fill-in-the-blank questions, and matching exercises do not exist in this text. Instead, the text develops big ideas through experimental work and careful interpretative work drawn from a series of related laboratory activities. These laboratory activities are the main focus of each section, and the brief narrative text that supplements the experiments cannot make sense unless students are doing the experiments. Text explanations and technical vocabulary are kept to a minimum. For example, the introductory text for Section 2, "Investigating an Interaction," starts by introducing the word "photosynthesis" and using it as an example of an interaction between plants and the environment. A brief definition of photosynthesis as the process by which green plants make sugar is given and is followed by directions that engage students in a series of five-eight investigations where they try to figure out more about photosynthesis as an interaction between plants and the environment. As the text explains:

> In your notebook make a list of things that you think might be involved in this interaction between green plants and their physical environment. How could you determine which things are necessary and which are not necessary for photosynthesis to occur? (Abraham et al., 1975, p. 28)

Thus, the emphasis is on interpreting experimental observations and using them to develop understandings of big ideas like photosynthesis.

Using these materials changed my understandings of biology in two ways. It changed my ways of knowing biology and what it means to understand biology, and it changed my understanding of particular pieces of science knowledge that I needed to know to teach well. My experiences teaching from IMB materials changed my way of knowing about biology by helping me develop an idea of conceptual connectedness--that there are "big ideas" in biology that can be connected in ways that provide a useful frame for organizing the myriad of details that are a part of biologists' knowledge, that there are many different ways of connecting biological concepts together, and that these frameworks of connections among big ideas can provide a beauty in their simplicity (in contrast with my earlier limited focus on the complexities of the living world). I had always assumed that biology was organized around levels of complexity of the organism--from one-celled organisms to simple plants to flowering plants or from one-celled organisms to invertebrates to vertebrates ending with humans--or around the different areas in biology such as plant or animal anatomy, plant or animal physiology, biochemistry, and ecology. Somehow I had missed the conceptual reasons for such organization in my high school and college textbooks--concepts like evolution, structure and function, interactions and interdependence, cycling of matter, flow of energy, the cellular basis of life.

Although I had studied all the concepts presented in the IMB materials in my science studies, its conceptual organization was strikingly different from any I had ever encountered before. It had never occurred to me that you could center your study of biology around a problem such as transportation in multicellular organisms and then explore the problem in both plants and animals simultaneously--comparing and contrasting circulation in plants and circulation in animals including humans. And this study of transportation problems in the IMB materials started with an exploration of cell membrane models and experiments investigating which materials can and cannot get through cell membranes. I was used to studying cells in the first chapter of the text or the first week in the biology course and then just assuming their existence but essentially forgetting about them as I explored other topics in biology like photosynthesis or blood circulation. But the IMB materials highlighted the idea of cell in a study of how the problem of transportation is solved by plants and animals.

This organization raised new questions for me and new appreciations of the wonders of biological processes. I found myself more appreciative than I had ever been before of plants' ability to circulate materials--I don't think I had ever really stopped to marvel at this process or to think there were questions left to explore when I read about it in extreme detail in my plant physiology course. But somehow studying it at a more "basic" level (in terms of numbers of details given), studying it in comparison with human blood circulation, and studying it in the context of linking it to a just-completed probing of the processes of photosynthesis in comparison with human's digestion, I had a new level of awareness of the complexity of the problem. I found myself wanting to know more and understand better how it is possible for huge trees to circulate materials without a pump like the heart. And for the first time I really connected the idea that plants use the materials they create in photosynthesis for their own nourishment. I had certainly "learned" that many times before, but for the first time I had a mental image of that happening inside plants just like I had an image of food circulating and being used in cells in my own body. I felt more connected to plants. Most importantly, I had a new way of looking at biology--looking for patterns and connections and big ideas--and I recognized that there could be multiple ways to organize biological knowledge to serve various purposes. I became curious about the kinds of organizations that would make the most sense for learners.

The interconnectedness between the text and the investigations in the IMB materials also influenced my thinking about what it means to know science. Because of the text organization, I began to question the relationship between two areas of science that had always been so distinct in my experience: the laboratory and the lecture, the processes and the content. I began to see how a series of investigations could be linked to each other in the service of trying to construct an understanding of science concepts. In this regard, I found myself engaged with students in a series of experiments that supported us in constructing together an equation to represent photosynthesis. The equation was not given to us in the text, and the version we created differed from the detailed equations I had memorized in my college courses. But it was a meaningful equation that grew out of our experimental work and that accurately captured the "big ideas" involved in photosynthesis. This experience represented a first step in challenging my notion of science as divided into content and process categories.

Teaching with these materials also gave me a different way of thinking about the usefulness of biological knowledge. As I became aware of how the curriculum was helping me develop new and more personally meaningful understandings of biology, I realized that usefulness of scientific knowledge did not only belong to the expert scientists. Scientific knowledge could also be useful to the individual. I witnessed this personal usefulness in my own relearning of biological concepts and occasionally in my students' learning. I still remember vividly the day that one of my hardworking but "average" students burst out excitedly, "Oh! I get it!," and then proceeded to ask a series of questions that showed she was applying her new-found understanding of how body systems work together to get food and oxygen to cells all over the body. "Is that why..." So does that mean...?" I saw the power of these connected frameworks of ideas to help students and myself develop new understandings of everyday biological phenomena. Because this kind of understanding only developed in a few students, I knew that the conceptual frame was not the only knowledge necessary to teach science well, but I was convinced that it was a critical piece of knowledge of science for teaching.

This teaching experience also helped me develop new conceptions of the relationship between conceptual knowledge in science and the scientific processes. The two now became very closely linked in my way of understanding science. In particular, I came to appreciate how scientific investigation can support the development of conceptual understandings. All of the major ideas embedded in the IMB text were developed from experiments and models which were often supplemented by descriptions from the history of science that gave me a new picture of knowledge growth in science. Experiments in the IMB materials were not isolated "hands-on" activities or nice activities to supplement the text. The text consisted of closely linked chains of related investigations with interspersed text designed to help the student pursue questions and concepts through the investigations. This helped me see how an experiment can provide tentative or partial answers that often lead to another question, another experiment, another model.

My teaching experience with these materials also gave me an understanding of particular things I needed to know that were certainly part of science but that definitely had not been a part of my academic preparation in science. Most salient to me was that I needed much better understandings of how biological concepts could be useful in explaining everyday experiences that students encounter. My students did not ask the kinds of questions that were answered in my college biology texts: What are the steps in photosynthesis? in the Krebs cycle? What are the parts of the cell? Instead they asked: Is blood really blue? How long does it take oxygen to get to your cells? What causes hiccups? What do snails eat? Do they have stomachs? Can they eat the dead fish in our aquarium? Do plants do better when you play music? I needed to know a lot of specific information about real-world applications of the big ideas developed in the text, not necessarily so I could answer all of these questions but so that I could evaluate students' questions in terms of the concepts being studied: Is this a question that students can begin to answer using knowledge they are developing? Is this a question that students can explore themselves in meaningful ways? Or is this question totally unrelated to the web of concepts we are weaving? How did the students' questions connect with important biological concepts? How could I help them explore their questions in ways that would not simply give them a quick answer but enrich their understanding of biological concepts and processes?

Although the IMB materials changed my own understanding of biology, this learning did not help me define clearly what I wanted students to learn and understand about science nor did it help be reflective about my teaching and my students' learning. I used these materials for four years of my teaching experience, and yet it was only during the first year that the materials challenged my knowledge of science in significant ways. After that first year, I felt like I had figured things out, and I did not question my teaching or my students' learning in productive ways. I remember for example, a parent coming up to me at the fall open house after hearing my description of my goals for science. He said to me, "Do you think you can really teach someone to think scientifically?" His question caught me off guard, because I had never stopped to think about how you could actually teach someone to think scientifically. In fact, I had never stopped to think about what I meant by "scientific thinking." I had claimed a teaching goal that I had not seriously thought through. In retrospect, I am astonished that his question did not get me thinking about what I really meant by "scientific thinking." Even after his question, I taught for several years without having a clear notion of what kinds of understandings of science I wanted students to have.

My description in my formal teaching documents from those years focus on "appreciating the natural world" and "learning to think scientifically." However, my teaching practice, as recorded in my plan books from 1972-1977, focused more on content goals--teaching kids about the ocean, chemical changes, how mountains are created, photosynthesis--than on appreciation and scientific thinking goals. These I assumed would develop from students' participation in scientific inquiries, from nature walks, birdwatching projects, weather forecasting projects, terrarium building, and our eighth-grade weeklong backpacking excursion in the mountains of West Virginia. As I look back, I realize I knew a lot about what grades students had earned and how they earned them, but I knew very little about students' understanding of various aspects of science.

And it never occurred to me to look hard at my teaching and my students' learning. It never occurred to me that I would continue to learn about science and about science teaching and learning as I continued to teach. In fact, I consciously thought about how I had pretty much "mastered" teaching after about three years of experience. The learning was pretty much finished, I thought. Learning about teaching and about science from this point on was just fine tuning.

This need for fine tuning led me to pursue doctoral study. A minor irritation in my teaching had been my frustration with science textbooks. I wanted to understand better how to help students use texts more effectively, and I wanted to learn how to create new kinds of textbooks that might be more comprehensible to students. I entered graduate school to pursue these questions and soon found myself back in the classroom but in a new role--a researcher role. This role had a dramatic impact on my thinking about science and on my view of the role of inquiry and learning in teaching.

Transforming Science Knowledge to Science Knowledge for Teaching--Lessons Learned from Research

My thinking about the science knowledge needed to teach underwent a dramatic change as a result of my experiences in a series of research studies in which I had the luxury to observe and study teaching. I observed upper elementary and middle school science classrooms for extended periods of time (3 to 6-week units) and assessed both teachers' and students' understandings of the particular concepts/topic being taught. Assessment strategies included extensive pre- and posttests of student understanding as well as clinical interviews with both students and teachers at selected points in the progress of the unit being observed. Analysis of the teachers focused on their knowledge of the particular topic being taught (photosynthesis, light and seeing, respiration, ecosystems) and identifying ways that knowledge was used in planning (the intended curriculum) and during instruction (enacted curriculum). Analysis of the students focused on tracing changes in their understandings of the topic (beginning with the pretest) and how instruction influenced changes in their thinking.

Most of the teachers involved in these studies were selected because they had good reputations as science teachers and because they had a high interest in teaching science well. In one of the classrooms I observed, I remember being particularly impressed with how the teacher engaged her students in being “little scientists.” Using the activity-based

Science Curriculum Improvement Study materials (SCIIS, Knott, Lawson, Their, & Montgomery, 1978), Ms. Kain had students performing controlled experiments to find out how plants get their food (Roth, 1984). Students collected data on plants growing in different environmental conditions - they wrote observations about the plants and kept graphs charting the growth of plants in the different conditions. Class discussions elicited students' interpretations of the observations. Ms. Kain rarely gave the students the "right" answers; she expected them to make observations and to come up with good explanations and interpretations. Her classroom was a lively place with students busily collecting data and sharing their explanations and ideas--in many ways their work was like the work of laboratory scientists.

I thought this was excellent science teaching that would teach students much more about the nature of science than the textbook-focused instruction I had observed in other classrooms. However, analyses of student learning convinced me that in both types of classrooms (activity-based and textbook-based), meaningful learning was only occurring for a few students. Most students entered instruction holding their own ideas about how plants get food or about how light enables us to see, and these entering conceptions drove students' interpretations of instruction. The large majority of students in Ms. Kain's classroom, for example, began and ended instruction holding their experience-based conceptions that plants get food much like people do--by taking it into their "bodies" from outside themselves--in the case of plants from the soil. The students either ignored the concept that Ms. Kain wanted them to develop about plants using raw materials from the environment to produce internally their own food or they incorporated it into their personal theories in unintended ways (plants need to get different kinds of food just like we do--they can use water and soil or they can make food). Without an appreciation of plants' unique ability to transform nonenergy-containing matter into energy-containing food, what sense could students possibly make of the next unit about the critical role of plants as producers in ecosystems?

I was also struck by ways in which the students' regular engagement in scientific processes failed to help them develop meaningful understanding and appreciations of the nature of science. In interviews, students talked about how the experiments had been "fun" at first but that after awhile it was tiring measuring plants all the time. As Rachel explained: "I don't know *why* we kept measuring those plants. I mean it was fun for awhile, but I already know that plants need light to live, and now I know it again." (Roth, 1989-90, p. 20)

Acting like a scientist had not been meaningful for Rachel and many others. Keeping track of the plants in four different experimental conditions, using the rulers accurately, plotting the graphs, had been challenging tasks that took place over a number of weeks. Students lost sight of the point of it all. I came to understand that while this kind of experimental work might provide convincing evidence and support for the idea of photosynthesis to scientists, for many learners of science it was not a meaningful exercise. It did not support them in changing their ideas and developing better explanations about what is going on inside plants. Instead, many students learned that science is all about measuring and graphing, and that "doing" these kinds of activities is what science is all about. They did not perceive any usefulness for all this activity--it was just something that scientists, for some unknown reason, do.

These classroom research experiences provided me with several insights about the knowledge of science needed for teaching. First, it pushed me a step further in my understanding of the relationship between what had traditionally been divided in my experience with science: content and processes, lecture and lab. I saw the dangers of representing science as primarily content in the text-based classrooms and as primarily processes in the activity-based classrooms. But it was this latter insight that most dramatically changed my thinking about the nature of science. I had found myself leaning towards a process view of science as I watched students in these activity-based classrooms and compared their experiences with my own experiences in very knowledge-focused, memorization-oriented science classes. Their experiences looked so exciting and inviting! But close examination of learning in these settings convinced me that the students were developing a distorted view of science, a view in which they could become frustrated and alienated from science because of its mysterious love for predicting, measuring, recording. For students who failed to learn how to use these processes to develop richer explanations and understandings of the world around them, these processes of science only reinforced their belief that they could not make sense of science. They felt just as lost in this foreign culture of science as the students in textbook-oriented classrooms who memorized vocabulary terms without understanding the usefulness of those terms in explaining the world around them.

Second, this research convinced me that it is not enough for the teacher to see the connections among ideas and to be able to distill from that the "big" ideas. It is not enough to be able to transform knowledge of science into a simplified and coherent story line. Teachers also need to know about how these big ideas and "stories" connect with students' own experiences and ideas about natural phenomena. Ms. Kain, for example, understood that the central issue that students should understand was the idea that plants, unlike animals, could use energy from the sun to make their own food out of water and air. She was not trying to shove mountains of details about the cell structures of leaves or about the steps in photosynthesis into her students' heads. She had a simplified and coherent conceptual framework, and she understood how the experimental work supported this conceptual frame. However, she initially did not know about the ideas that her students held that were in conflict with this scientific conception. And as she became aware of her students' alternative ideas, she did not appreciate the role that these ideas were playing for students in their interpretation of instruction.

What proved helpful to her in teaching this unit to a different group of students the following year was a new story line that we developed and built into a revised version of the SCIIS activities (Roth, 1985). This story line emphasized throughout the relationship between students' entering conceptions and the scientists' conceptions. Although the instructional unit was cut down from 23 lessons in Year 1 to 16 lessons the following year, Ms. Kain's students were much more successful in undergoing meaningful conceptual change in the second year. For example, in answering the question, "What is food for plants?," only 7% of the students in Year 1 used the idea that plants get their food only by making it. On the second year posttest, 79% of the students answered this question by referring only to photosynthesis or plants' making of food. This provided convincing evidence that knowledge about students' thinking in science and its relationship to scientific conceptions are critical pieces of knowing science for teaching.

A third insight that this line of research provided for me was that the kinds of work that might be useful to scientists in developing meaningful understandings is not necessarily the same kind of work that is meaningful to students. In my teaching of Kelly about plants' making of food and about what happens to food after we eat it, I often made decisions to eliminate the most scientifically elegant, controlled experiments because of my understanding about how kids think about plants and about their own bodies. In selecting tasks for my students, I had to consider what would "work" in the sense of helping them change and improve their thinking about plants or body systems. Often, the scientifically "correct" controlled experiments required students to keep track of so many variables that I felt that students' attention was focused on that challenge rather than on using the data to make sense. In contrast, I found role playing, a task which may seem nonscientific, to be an interesting and meaningful kind of work for students like Kelly.

Students wrote and acted out mini-plays about a "baby" plant's life or about the life of a human body cell. While important scientific issues came up in this work (such as students realizing that no one body structure or body system was the "star" of the cell play, that all parts are absolutely critical), it was an activity that many disciplinary experts might reject as inappropriate and non scientific. I would argue that knowledge about students and what will help them develop meaningful understandings and appreciations of science may often require teachers to move outside the bounds of disciplinary science and disciplinary views of scientific inquiry and knowledge growth. I found role playing to be a more effective "model" of human body systems, organs, and interactions than more traditional anatomical models of the internal body organs and systems. Having students act as "little scientists" is not necessarily what will be most helpful to them in developing meaningful understandings and appreciations of science. The teacher has to analyze the particular concept being developed, the students' ways of thinking about that concept, how students learn, and the variety of ways (both disciplinary-bound and otherwise) that the concept might be developed or represented. Decisions need to be made from this web of factors and this requires a very flexible knowledge about science and science inquiry.

Finally, this work convinced me that inquiry and study of teaching--and especially careful study of student learning--could yield insights of critical importance to me as a teacher. For the first time I saw that research was not just important for researchers, to build their reputations and careers. Now I saw that the intertwining of research and practice could support and change teaching in ways that would make differences in terms of the quality of student learning. This was a key development in my professional career, a transformative event that has had a lasting impact on my teaching.

Transforming Science Knowledge to Science Knowledge for Teaching--Lessons Learned from Philosophy of Science and Cognitive Science

Another trigger for changes in my own knowledge about science was my engagement in a formal study of philosophy of science and cognitive science concurrently with my involvement in the classroom studies of science teaching described above. This formal study and the opportunity to consider these theoretical perspectives while observing classrooms helped me see interesting parallels in knowledge growth in science and in individual learners. These new understandings gave me a new framework for thinking about the nature of meaningful science instruction.

My study of philosophy of science helped me change a simplistic, empirical model of knowledge growth in science in which scientific concepts, principles, laws are discovered by rational induction based on observable, objective facts to a much messier constructivist or hypothetico-deductive view. This constructivist perspective emphasizes the ways in which scientists' knowledge and theories interact with their experiences and observations of the real world. It paints a much richer, more human view of knowledge growth in science. In this view scientists' existing knowledge has a critical influence on the ways in which they observe and perceive the natural world; they can never be purely objective. Scientific theories do not grow directly from observation but are constructed by humans who are constantly testing and evaluating their conceptual frameworks against actual data from the real world. Expert scientists do not hypothesize, observe, make inferences, or design experiments in the absence of conceptual frameworks. Their conceptual frameworks are not only influenced by their observations and inferences; their frameworks also drive and shape the hypotheses they make, the questions they raise, the things they pay attention to in their observations. What distinguishes their work as science is not these processes, which are processes equally applicable in history, economics, mathematics, or the arts, but the particular knowledge that organizes how these processes are used.

A scientist who observes well, for example, is not one who spends endless hours documenting and describing every possible detail that can be observed about a particular phenomena (an activity I used to have my seventh graders do in science!). In contrast, a good scientific observation focuses on key features in ways that will contribute new knowledge, increase the explanatory power of a particular conceptual framework, generate new understandings of relationships among concepts, or raise significant questions about accepted conceptual frameworks. To make such observations, the scientist draws from existing conceptual knowledge, asks questions about important pieces of the framework, develops hypotheses, and designs experiments that will permit the critical and relevant observations to be made. The importance of the observation is not how accurately the scientist can detail and describe all facets of the observed phenomena, but how the scientist uses the observed phenomenon to develop more powerful and complete explanations--in how useful the observation and the scientists' interpretation of the observation is in refining, changing, and challenging conceptual frameworks shared by the scientific community. As Millar and Driver (1987) argue, science processes are not meaningful in isolation, and they are not science in the absence of a scientific conceptual framework. Thus, scientists' conceptual frameworks are at the heart of the scientific endeavor; they both drive and limit knowledge growth in science.

My study of cognitive science and concurrent studies of learning in classrooms helped me undergo a similar change in my understanding of what it means for children to learn science in meaningful ways. Studies of expert/novice differences highlighted the importance of conceptual frameworks in learning, reasoning, and problem solving. Experts are not expert because they have highly developed, abstract reasoning skills; rather, the research suggests that experts are able to reason in expert ways because of the well-structured and functional knowledge of specific content and concepts in a particular domain (Glaser, 1984). Glaser's review of this research points to several studies that show how children's or novices' abilities to reason at abstract levels are improved as a result of new conceptual knowledge. He concludes that conceptual understanding is at the heart of what is traditionally called higher level thinking or problem solving. I interpret his view to suggest that it is misleading to characterize a "knowledge" level of understanding as being "beneath" higher level thinking (as in Bloom's taxonomy of educational objectives; Bloom, Hastings, & Madaus, 1971). Developing understandings of scientific concepts and explanations requires higher level thinking to generate the knowledge. The idea that an individual's knowledge structure drives the kinds of reasoning he or she is capable of doing is parallel to the description of knowledge growth in science described above.

Study of philosophy of science and cognitive science helped me develop new understandings of science that were critical in my teaching. First it gave me a way of thinking about the relationships between content and process goals in science teaching.

Instead of planning my teaching so that students would learn both process skills and content in a kind of checklist approach, I became aware of the importance of focusing on the development of students' conceptual development, using scientific processes in ways that would make that development one characterized by significant change in the learner's conceptualizations. In teaching Kelly, for example, my focus was on helping her undergo meaningful changes in her personal thinking about natural phenomena. The focus was on supporting her growth in understanding, not on making sure I taught her to make careful observations or to learn how to formulate hypotheses. Instead of choosing tasks that would explicitly teach Kelly about process skills, I chose instructional tasks that would engage her in using process skills to support her conceptual change. In retrospect, I can identify a variety of process skills that Kelly and her classmates used, but the important thing to me was not that they learned to use process skills but that they learned that these process skills were useful in helping them develop better understandings of the world around them.

Second, studies in philosophy of science and cognitive science changed my understanding of how difficult it is for both scientists and students to break away from accepted conceptual frameworks. In my teaching this led to a much closer assessment of what students were really thinking and understanding as my instruction progressed. I had a new appreciation of the challenges, difficulties, messiness of learning in both the individual and in science. Conceptual change in science and in the individual is not a straightforward process; it takes time and many opportunities to work through ideas and to talk with others about developing ideas. I no longer attributed learning failures to students' failures to work hard, to listen, to complete assignments. I now had a new understanding of the difficult cognitive work I was asking students to do and of the need for the teacher to scaffold and support that process carefully.

Using My Transformed Understanding of Science to Teach Kelly

All of these transformations in my knowledge of science played critical roles in my teaching Kelly about how body systems work together to get food and oxygen to cells. Below are illustrations of ways in which my new understandings of the connectedness and usefulness of science knowledge were critical in my teaching of Kelly's class. I also describe how new appreciations of knowledge growth and change both in science and in science learners had an impact on my teaching. Finally, the ways in which the social nature of knowledge growth within a scientific community was translated into my teaching are described.

Science knowledge is connected. Changes in my understandings of the importance of connectedness in science enabled me to construct a coherent story about the very complicated concept of cellular respiration. I was able to simplify the scientists' story but still keep the big ideas in focus. To do this, it was not sufficient to know all the steps of the Krebs cycle. It was not sufficient to be able to describe all the structures and functions of cells or to explain how enzymes are synthesized and used in the digestive process. I had to have the kind of knowledge of science and of these particular topics and concepts that would allow me to sift through all these details and the details in my students' textbook about all of the different structures in each body system and find a coherent story line that was simplified and accessible to the students, that would be useful to students in making sense of a variety of phenomena, and that was also faithful to the discipline.

In selecting an organizing story line, I had to understand the different ways in which the discipline organizes and frames ideas. What are the big ideas, and what are the multiple ways in which they relate to one another? One way to organize biological knowledge, for example, is to consider different groups of organisms one by one in a taxonomic review of the living world. Had I selected this organizer, I might have begun the year with a unit on plants that focused on the diversity of plant structures and functions rather than on photosynthesis. I could have used the diversity and structure/function themes to continue studies of each animal group. The study of body systems would have focused on comparisons of humans to other groups of organisms. Instead, I decided to focus on food and energy as organizers across several biological units. I made this decision partly for disciplinary reasons: this organizer enabled a focus on critical biological issues that also cut across other science disciplines (for example, it connected with changes in matter and chemical change in chemistry, and energy and light in physics). To make this decision about a food and energy focus, I had to understand that knowledge about body systems was intimately linked with knowledge about cells and cellular respiration. It was this kind of connectedness of my knowledge that helped me select the digestive, respiratory, and circulatory systems as the focus of the unit instead of the textbook's emphasis on an "all-about" review of the body systems.

Thus, part of finding a coherent story line for this unit depended on understanding the ways in which the discipline organizes and frames ideas. Equally important, however, was my knowledge about how disciplinary organizers connect with students' ways of thinking. I strove to weave a story in a way that connected with how my students think. I drew from all the details I knew about body systems and cells and from my understandings of fifth graders' ideas about the body to pick out concepts or big ideas that I thought would foster significant conceptual change for the students. I wanted to choose ideas that would challenge them but still be accessible to them in a meaningful way. For example, I knew that students tend to think about food simply coming in the front door (the mouth) and going out the back door (the anus). They seemed to have no need to explain why this happened except that it kept us alive. I thought that a focus on what happens to food in the body would deepen their understandings of structure/function relationships and would also challenge their tendency not to consider the whys and hows of unseen processes (in humans in this case). As I got into teaching the unit, I found that students were focusing their attention on learning more details about the different organs through which the food passed while persisting in their view of food as moving through the long digestive tube from mouth to anus. They had already learned these facts in fourth-grade health class and were convinced they "understood" digestion. But the "in-and-out" theory of food remained firmly in place despite my explanations that food goes from the small intestines to the bloodstream to be carried to cells all over the body.

To help students understand how body systems work together to get food to the cells all over the body, I decided that it was critical that they be able to visualize an unseen process--how digested food could get out of the small intestines in a way other than going down the tube to be eliminated. A turning point in many students' understanding was the discussion of a digestive system model that we constructed in which the small intestine wall was made of a screen. I taught the students the word semipermeable to describe cell membranes and the small intestine wall. This word and the notion of a screen became meaningful to most students. Now they could imagine how food could get out of the small intestine other than through the opening at the end of the tube. Later they used this idea in constructing a skit about how food travels to the body and eventually gets to the cells. In their play, the student playing the part of the cell was wrapped in a volleyball net while students playing the part of the bloodstream walked by passing into the cell small bits of food. It was not until they had worked through these activities that students could make sense of the simplified explanation that "food goes out of the small intestine and into the blood and then to all the body cells." It was not enough for them to have a simplified explanation. That explanation must also connect with students' thinking and the difficulties they have in making sense of particular ideas and concepts. I had not originally planned to introduce the idea of semipermeability of cell membranes to these fifth graders--it sounded too complex!--but it turned out to be an idea that was helpful in enabling students to imagine better images (models) of what was going on inside their own bodies.

Science knowledge is useful. Another part of finding a coherent story line is knowing about the usefulness of the knowledge. An important part of scientific knowledge for teaching is knowing about a variety of ways in which particular concepts can be useful in explaining or predicting phenomena. Students need to see how new concepts can help them explain a wide variety of phenomena in their realm of experience. In my own teaching, the food and energy framework was selected for emphasis not only because it is a way that scientists organize concepts but also because I could see many instances of phenomena that could be explained by fifth graders in meaningful ways using the concepts of food, energy, body systems, and cells. For example, this knowledge enabled my students to explain how a growing fetus gets its food, what happens to medicines and drugs when we ingest them, how smoking can affect cells all over the body, why people have to have oxygen and food, how people are similar and different from other organisms, how plants "eat" the food that they make, how fish get oxygen into their blood, and so forth.

An important part of my planning for this unit was looking for questions and tasks that would allow students to practice using new ideas in numerous different contexts. In actually teaching the unit, I continued to be on the lookout for student experiences and stories that would provide opportunities to use the ideas we had been developing. As I encouraged and listened to students' questions, I had to have the knowledge to assess the usefulness of the tales the students told or the questions they asked. Which ones provided useful application opportunities? Sometimes I lacked the necessary knowledge (what does cause hiccups, anyway?), but I was able to build on others in useful ways. Students used their knowledge not just to figure out answers to my questions but to understand Brenda's father's heart operation, the efforts of Jim's mother to give up smoking during pregnancy, Ellen's mother's pregnancy, TV commercials that Jason saw about antacids, and April's bronchitis.

Science knowledge as constantly changing and growing. My new, constructivist understandings of how knowledge grows in science and its parallel in learners of science has had a dramatic impact on my teaching. This knowledge has given me an appreciation of how difficult it is for students like Kelly to change their ideas in meaningful ways and the need for them to have multiple opportunities to work with new ideas, to ask questions, to get careful feedback and thoughtful challenges to their thinking. This aspect of my teaching represents a dramatic change from my early years of teaching when I expected that understanding science was largely a process of listening carefully, studying hard, memorizing. In contrast with my early years of teaching, my teaching is now characterized by a continual assessment of where the students are in their thinking and by careful responses to students' ideas--both on-the-spot responses and responses in the form of future instructional plans. I also work hard to create tasks that will engage students in using their ideas and in talking about their ideas, not just listening. My goal is to give students the kinds of tasks and support that will help them make significant changes in the ways they think about natural phenomena in their world.

Science knowledge as jointly constructed in a community of scholars. No matter what kind of wonderfully coherent and useful story line I may construct, students cannot just listen to my stories and fill in the blanks. For them to make sense of the concepts, they must become active and interactive learners--talking, asking questions, writing down ideas, comparing ideas with classmates, getting feedback about their ideas from the teacher, arguing interpretations. For the conceptual story to be meaningful, it must become their story and not something I give to them. An aspect of my teaching about the human body was figuring out ways to have productive classroom interactions so that students were not isolated learners struggling to make sense without the support of input and feedback from others. A new kind of class discussion became important in my teaching. My goal was that discussions would have more of the characteristics of good scientific conversations instead of what we typically label as discussion in classrooms but that is really more appropriately labeled recitation: teacher question, student response, teacher evaluation of the response (right or wrong).

Part 3: One Student's Developing Knowledge Of Science: Brenda's Learning Across A School Year

In the 1988-89 school year I took on new two challenges in my teaching: (a) To draw from my new understandings of science and science learning to enable students to "really" understand (Gardner, 1991) a limited number of important concepts in science, and (b) To take on a researcher role in my own teaching, studying my actions and my students' learning in order to assess the impact of my new approaches to teaching. In Part 2, I talked about my efforts related to the first of these challenges. This section focuses on (b), examining what I learned about one student's learning across the year as a result of my teacher/researcher role. My study of Brenda's learning (and the learning of her classmates) both supported and challenged my focus on the centrality of conceptual knowledge in science. Analyzing the strengths and weaknesses in the view of science Brenda developed supported me in rethinking what is essential and critical in understanding science: What images of science was I helping her develop? How were these images of science helpful or not to her? Examining Brenda's understanding of science provided a tool for reconsidering my own understanding about the nature of scientific communities of inquiry.

I do not present Brenda's s understanding of science as typical of my students that year; in fact, if I told the story from each of the student's perspectives I would have to tell 29 different stories. However, Brenda is typical in terms of her engagement in class activities and in terms of her change across the school year. She is not a "straight A" student, a student who teachers would typically call a "star" academically. I present Brenda's case as one example of what's possible in terms of student understanding--what's possible for a girl who is turned off to math and science and who typically succeeds in classrooms by keeping quiet and working diligently to get tasks completed?

I start Brenda's story on the last day of school. In fact, school had been dismissed for the summer, but Brenda and several other girls who lived near the school were reluctant to leave. I soon had Brenda helping me take down the large time line that we had created and continually added to across the school year as a reference point for our study of

American history. As Brenda was taking the time line down, she talked about how sad it was to take it down and begged me to let her take it home with her. This activity stimulated Brenda's reflections back across her learning during the year. First, she commented about social studies (this is paraphrased from my journal entry; the tape recorder was not turned on during this conversation--B=Brenda, KR=author):

B: There was something in social studies I never got.

KR: What was that?

B: Ya' know the Puritans? They came to America for religious freedom but then they wouldn't let other people in their colony have any other religion than theirs. I don't get that. Why would they come for religious freedom and then not let others have religious freedom?

This comment struck me as an example of an important kind of understanding that Brenda had developed about social studies. Most strikingly, it showed her disposition to reflect on her knowledge about historical events and to try to make personal sense of them. A few minutes later, Brenda made a similar reflective observation about her science learning: "Ya' know, all that stuff we studied in science . . . it all fit together in the end, didn't it? That's neat!"

Here Brenda revealed--in ways that a test somehow cannot capture--the meaningfulness that she had constructed from studying science in this classroom. In this case, the most striking aspect of understanding that she is reflecting and valuing is "connectedness." But in recognizing and celebrating the connectedness of our science study across the year, she is showing much more than a set of understandings about how adaptations are related to photosynthesis which is related to cell respiration which is related to chemical change which is related to ecosystems and food chains which is related to energy, etc. (See the yearlong curriculum chart in Table 1). In addition, she is demonstrating the dispositions she developed in science to make sense, to construct new knowledge and connections and to view her own knowledge as building over time.

What was I able to find out from more formal assessments of Brenda's learning about the connectedness of her science knowledge, about her ability to use scientific

Table 1

Units and Concepts in the 1988-89 Science Curriculum

UNIT	ADAPTATIONS	INSIDE ADAPTATIONS – PLANTS	MORE INSIDE ADAPTATIONS- CELLS & BODYSYSTEMS	ECOSYSTEMS - MATTER CYCLING AND ENERGY FLOW	RAINFOREST ECOSYSTEM
When?	September - October	October - November	December - February	March - May	May - June
Central Question	How are plants, animals, & people adapted in different ways to survive hot, dry weather conditions? What structures do plants have that enable them to get/conserve water? How are animals adapted in different ways to get food?	How do plants get their food? (Why do they need water?)	Why do you need to eat and breathe? (What happens to food you eat? to the air you breathe?)	What are different ways that living and non-living things interact in ecosystems? (Why do plants need fertilizer? What happens to something when it dies?)	How can people cause/solve problems in ecosystems?
Main Concepts	Structure Function Adaptation Diversity of Adaptations/Structures in both plants and animals	Compare how plants and animals get food Photosynthesis Changes in matter Sun energy changed to food energy Food	Systems - digestive, circulatory, respiratory Interactions Structures Functions Cell respiration - how each cell gets food & O_2 to release energy from food Energy changes (food Energy ---> usable energy) Comparing plants & animals (Use of animals in scientific research)	Chemical changes - photosynthesis, respiration, decomposition Matter changes Energy changes Food chains- producers, consumers, decomposers Populations Species Cycles	Diversity Species Extinction Balance Human Needs Effects of cutting on food chains, photosynthesis

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knowledge, and about her developing dispositions to participate in a scientific discourse community and to view science knowledge as continually changing and raising new questions (see Figure 1)? In the next three sections I provide a sampling of different methods of assessment that provided insights about Brenda's understandings of science, and I use these insights to analyze both the power and the limitations of her views of science.

Connectedness of Brenda's Understandings in Science

Pre- and posttests for each unit of study, interviews at the end of the fall, at the end of the school year, and a year later at the end of sixth grade probed students' ways of organizing concepts they had studied in fifth grade science. One particularly useful assessment tool was a simplified concept map, which I called "word pictures" with the students. At the end of the photosynthesis unit in November 1988, Brenda arranged her concept cards and explained them in ways consistent with scientists' views about photosynthesis:

Photosynthesis

embryo ---> cotyledon ---> air ---> sun --> leaf ----------------> water ---> roots
food ---> tubes ---> stem --> store ---> fruits & vegetables ---> energy --> fertilizer

B: The embryo when it's just a baby eats the cotyledon. Once it's a full grown plant it uses air and sun which goes into the leaf through holes, and water which goes into the roots, to make food. The tubes are in the stem.

KR: Is there any connection between the food the plant makes and the tubes?

B: Uh-huh. Food travels to different parts through the tubes.

KR: Like where would some of these parts be?

B: Well, that's where I'm at. Food travels through tubes to the stem and it stores it in fruits and vegetables in the roots, and that's energy for the plant. But fertilizer doesn't have energy. The food is energy. Fruits and vegetables are food for us, and the food is energy for the plant. Fertilizer doesn't have energy.

KR: Okay, now you've put all of that together, I don't remember if you mentioned, how did photosynthesis work into this, Brenda?

B: Um, air, sun and water, the process that it makes food is called photosynthesis.

KR: Okay, and where does that take place, photosynthesis?

B: Inside the plant in the leaves.

This explanation stood in contrast with the kinds of explanations about how plants get their food she had given on the pretest (students' writing is unedited) in early October:

Pretest: Describe what food is for plants.

B: Fertalizer is for plants it is powtery and you add it to water and pour it on the plant.

Pretest: Do green plants need food to live and grow? Why or why not?

B: no & yes. no they can live with out food Yes if you do feed them fertalizer they will grow better and look prtter.

Brenda entered our 6-week exploration of how plants get their food holding a strong belief that fertilizer that people give to the plants ("feed" to the plants) is the plant's food and that the plant really doesn't need food; it just helps a little bit to have this food. Her explanation at the end of the unit provides strong evidence that Brenda has learned the story of the basic ideas involved in photosynthesis. She indicates an understanding about how the young plant first gets food from the cotyledon and later is able to use air, water, and sun to make its own food in the leaves. She has also connected this explanation of photosynthesis to her prior beliefs about how plants get their food, changing her mind about fertilizer and firmly asserting that fertilizer is not food because it doesn't have energy.

But does she really understand? Or are these seemingly well-connected understandings just memorized ones that will quickly be lost to her? How strong are the connections she has made to her way of thinking about real plants and how they work? A week before the posttest and this interview, Brenda had filled out a "ballot quiz," on which she captured her current thinking about sources of food for plants by responding "yes" or "no" to a list of eight possible sources of food for plants. For both "fertilizer" and "plant food from the store," Brenda wrote "no" along with her reason: "you told us it wasn't I don't remember why." In our class Question Notebook, she had entered the following questions about soil and fertilizers:

10/24/88 If the plants don't use the soil, Why do they need it?

11/15/88 How come the plants need minerls

Her persistence in raising questions about the role of the soil and minerals and fertilizers in plants suggests that the reason given in class (fertilizers are not food because they don't contain energy) was dutifully memorized but was not a convincing explanation to Brenda. Instructionally I looked for explanations that would make more sense to Brenda; in the ecosystems unit in the spring I baffled many students but connected with Brenda in showing how elements like nitrogen in fertilizers can be used by plants to turn the sugar made in photosynthesis into proteins that can be used to build new cells. Thus, the minerals in fertilizers (like nitrogen) are needed to turn food made during photosynthesis (sugar) into different forms (proteins) that can be used for building new cells and cell structures.

The year-end interview provides stronger evidence that Brenda has developed well-connected understandings--not just memorized ones--and that she has connected these ideas to her earlier thinking that fertilizer is food for plants. In this interview, students were given concept cards representing 45 different terms that had been used in science across the year. Students were asked to organize all these terms (or as many as they could) into a "word picture" that made sense to them. Students had not been given a similar task in class, and, in fact, there had not been any explicit mention in class that all the ideas we had studied could be related to each other. Thus, this was a challenging and novel intellectual task for the students. They had no warning they were going to be asked to do a "review" task or test of any kind. As a teacher I worried that this task might intimidate and frustrate students; I approached it warily. But Brenda, like every student who was asked to do this task, was not in the least frustrated by it. It took her a while to complete the task, but she approached it with confidence and proudly announced when finished that she had been able to use all of the cards. Below is her "word picture" and her explanation of it. Note how she now was able to place photosynthesis in the context of food chains and ecosystems and how her idea about "air" being needed for photosynthesis has become more differentiated (oxygen and carbon dioxide in air are used for different purposes by plants):

light energy
sun
air--oxygen
    carbon dioxide
water
food energy
sugar
plant
producers
cells   food
tubes in stem
sun & air
leaf
roots
photosynthesis
consumers--herbivores
rabbits
corn plants
consumers--carnivores
coyote
food chain

humans
    circulatory system
    digestive system
    respiratory system
    lungs
    small intestines
    blood vessels
cells
    cell respiration
    structure
    organisms--plants, animals, people

    functions
    cycles
    minerals
    co2

matter
decomposers
bacteria
ecosystems

B: Okay, light energy, sunlight energy, and air--carbon dioxide and oxygen is in the air--and water makes sugar which is food energy for the plants. Plants are producers. In the plants are cells and tubes which the sun and air go in the leaf and the water goes in the roots and up the tubes. And this process is called photosynthesis. Now, consumers, the herbivores, like a rabbit might eat a corn plant and the consumer, carnivores, like a coyote, might eat the rabbit. And this is called a food chain. Humans have circulatory systems, digestive systems, respiratory systems. And the large and small intestines, in the small intestines they have blood vessels which carries the food to the cells which is over here [she moves the "cells" card from the plant list to the humans list] and the cells do cell respiration. Now, all of these things [points to lungs, small intestines, blood vessels, cells] are structures of people and these are organisms.

KR: What are organisms?

B: The plants and the animals and the people. And organisms do functions and functions move in cycles and so do minerals. Functions are the way something works. Functions sometimes move in cycles, sometimes they move over and over again like different chemicals mixed together. They are always doing a function. They move in cycles and like minerals, and carbon dioxide, they move in cycles too. And when matter dies, am I going too fast?

KR: It's all right.

B: When matter dies, it's decomposed by decomposers. One kind of decomposer is bacteria and this all happens in an ecosystem.

Brenda's conceptual organization reflects an accurate understanding of the main ideas she studied in science class, although her explanations leave us wondering about how clear she is about things cycling in ecosystems (what does she mean by saying "functions" can cycle?). Her organization also does not tell us whether she made connections between plants (her first column) and humans (her second column)--they are organized and discussed as separate categories of information that are linked only by "food" and "cells." Finally, her explanation does not tell us whether she connected this set of explanations to her initial beliefs that food for plants is fertilizer that plants take in from the soil. The follow-up questions provided an occasion for Brenda to connect cell respiration in humans with cell repiration in plants (the idea that all living cells must receive food energy and oxygen in order to release energy from the food so it can be used for growth and other life activities). These questions also prompted her to elaborate her ideas about how matter cycles in ecosystems through a series of chemical changes and to connect this idea to her earlier beliefs about fertilizers. Unlike her November interview she now does not seem to be simply parroting (in a "I'll take your word for it" spirit) that "fertilizer is not food for plants because it does not contain energy." Instead, she has an explanation about the role that minerals do play in plants (protein building and cell building). [NOTE: **Bold emphasis below shows Brenda's connections between human cell respiration and plant cell respiration and photosynthesis.** Underline emphasis shows connections to her prior beliefs about fertilizer--places where she now appears to hold a belief that differs from her earlier belief]:

KR: What do plants take in from the air?

B: **Carbon dioxide and oxygen.**

KR: What do they use those for?

B: **They use oxygen to release the energy, and they use the carbon dioxide to make the sugar.**

KR: Is that any different from what people take in?

B: **No, but they [humans] get, the carbon dioxide goes right back out of people, we can't use it at all.**

KR: How does the plant eat the food?

B: **It [food] goes into the cells and it [the plant] uses it [the food] for food. . . . Oxygen goes in there and releases energy from the food.**

KR: Oxygen goes in the?

B: **The cell.**

KR: How does all that stuff get to the cell?

B: Through all of the veins and the tubes that it has. The water goes down into the soil up into the roots and tubes. And the sun and air goes in holes in the leaves.

KR: So where does it make the food?

B: It makes the food in the leaves, I think.

KR: And then after it makes the food, what does it do with it?

B; It sends it to the little tube that's down here and everything, and it sends it to the little cells all around it, and it also goes into the roots for storage. The cells would die if it didn't have energy.

KR: Sometimes people give fertilizers to plants. Is that food for plants?

B: No. Because it's got no energy in there [in fertilizer] for the plant to use. It makes its own food. [The minerals] helps it get stronger and it helps it make proteins and it helps it grow and helps the structure of the plant.

KR: Okay, plants in the woods don't have people coming along and sprinkling fertilizer on them, so how do they get minerals?

B: They get minerals from the soil like nitrogen, things like that.

KR: What would happen if plants in the woods used up all the minerals in the soil?

B: I guess they [plants without minerals] would probably live because they have food, but maybe they wouldn't be so healthy.

KR: Does that ever happen in the woods that the minerals get all used up from the soil?

B: No. Because it [the minerals] keeps rotating around and around and around and around. The chemical changes--like nitrogen just keeps going around and around in a cycle and they never die.

KR: So can you tell me how the minerals could get back in the soil?

B: Maybe the plant, that plant that's out in the forest and it dies and it gets decomposed, and the minerals go back into the soil. [The stuff that was part of the plant] goes back into the soil and some of it gets eaten up by bacteria.

In sixth grade Brenda attended a middle school where she had different teachers for each subject area, including science. I had no interaction with Brenda during the year, but I did hear from her mother that Brenda was quite indignant that her science teacher told the parents at open house that she would not be covering photosynthesis even though it was in the book, because photosynthesis is too hard and abstract for sixth graders to understand. Brenda visited my office for an interview at the end of the sixth-grade school year. At that time she was given the same interview task with the concept cards that she had been given a year earlier. It is fascinating the ways in which she again connected these ideas together in sensible ways, yet her organization was quite different than a year earlier. This suggests that her organization of the concepts was not simply a well-memorized pattern of words but rather a set of ideas that made sense to her and that she could use flexibly. Instead of grouping her words into discrete plant, human, and ecosystem groups with limited connections among them as she had done a year earlier, she now used a more integrated storytelling organizational strategy:

sun light energy -------->	air carbon dioxide oxygen -------->	water -------->	sugar
leaf -------->	tubes in stem-------->	photosynthesis ----->	chemical change
minerals -------->	corn plants -------->	humans -------->	digestive system
small intestines ----->	blood vessels -------->	cells -------->	lungs respiratory system
circulatory system --->	cell respiration -------->	food energy	
producers -------->	food chain -------->	rabbits consumers-- -----> herbivores	coyotes consumers-- carnivores
cycles --------> ecosystems	decomposers -------->	bacteria -------->	decompose

ORGANISMS

B: Light energy from the sun and carbon dioxide and oxygen are something that is in air. Light energy, air, and water in the leaves produce sugar. And . . . allright, light energy goes to the leaves and oxygen goes to the leaves. And the tubes in the stem, well the water travels through them. And they make it [the food] in the leaves. And this process is called photosynthesis, and photosynthesis is a chemical change because all these things, they're chemicals, and they change into sugar. And it's also made into minerals. Part of the nutrients the plant makes goes into things like corn plants which humans can eat. And the humans eat things like corn and food goes through the digestive system into the small intestines through the walls of the small intestine into their blood vessels and to their cells. I think the circulatory and respiratory systems are kind of the same thing, aren't they? All right, they bring air into the lungs and blood vessels to cell respiration that releases energy from food. That can also--just like with humans--that can also happen with producers, with plants, and with animals. It starts out with producers and then consumers--herbivore eats mostly all plants like rabbits, and carnivore eats meat like the coyote. This is called a food chain and these are some the cycles. After animals die they're decomposed by decomposers. One of the decomposers is bacteria. They decompose animals that are dead. And all these things happen in ecosystems. And it's all about organisms.

KR: This part here about producers and ecosystems seems a little different than this part up here [about plants and humans]. Is it different? Or is it related in some way?

B: I think they could be related because producers are plants and carnivores, even though they're animals, they could be humans, and so they are kind of related. And people and plants also get decomposed. Things like animals--consumers--have the same sort of digestive systems we have, but plants don't. They're not like people and animals.

I have shared these concept maps and Brenda's explanations of them to faculty in science departments at Michigan State University (MSU) and at other universities and have received half-joking comments like, "I wish our incoming doctoral students could put things together like that!" This kind of integration of conceptual knowledge is not an easy task in science. The fact that Brenda could approach this task with confidence and that she could be flexible in her arrangements of the concepts at the end of fifth and sixth grades provides powerful evidence that she developed a well-integrated understanding of the concepts and was not just spitting back memorized facts

Usefulness of Brenda's Understandings in Science

Connected knowledge is not meaningful knowledge unless it can be used by the individual. Brenda's word pictures in science would not be very exciting if they were inert knowledge that she reels off in interviews and test situations but does not apply in thinking about real-world events and phenomena.

In science, Brenda talked about her view of the usefulness of scientific inquiry in an interview at the end of the year:

> People study science so they can learn about what's happening in the world . . . so we can study what's happening in the world so they can know what things to expect like what happens if the rainforests are all cut down they know what to expect in the world, how things are working. [Talks about different things scientists study and different places they study including outdoors] . . . It has to do with things outside school. Like there's scientists and science going on all around us, you know, and there's science also going on in school. But there's a lot of science going on outside, like the food chain and photosynthesis and all that stuff.

This statement reflects an abstract understanding about the nature of science--that science is useful in helping us understand and predict events in the natural world. Brenda recognizes science as an active process going on all the time all around us. But to what extent is she herself able to use her study of science to make predictions and explanations of phenomena around her? Was her knowledge abstract and removed from her experience (like mine had been in college)--disconnected from her own personal use of scientists' knowledge? In this section I will draw from written work Brenda did across the year and an interview about science conducted at the end of the school year to illustrate some ways in which Brenda was able to use ideas she studied about photosynthesis and food for plants. This is an interesting topic to look at, because Brenda's ideas about how plants get their food continued to change and grow even after the completion of the official photosynthesis "unit" in the fall.

At the beginning of the year, the class studied about plant and animal adaptations. Because there had been a severe drought the previous summer, we focused much of our study around desert organisms and how they are adapted for getting and conserving water. On the posttest for this first unit of science study, Brenda was asked:

> KR: Look at the photograph of Ms. Roth's lawn. This picture was taken after the drought this summer. Do you think grass plants are adapted to very hot, dry weather? Explain your answer in a sentence. (9/28/88)

Brenda: "No. No is because part of the lawn is dead."

At the end of the school year, Brenda responded in a very different way to a similar question:

> KR: Last summer we had really hot, dry weather and people called it a drought because we had no rain for so long. A lot of grass plants and other plants died. Why do you think this happened? (5/30/89)
>
> B: Because they didn't have any water so they couldn't do no photosynthesis. Because they need water, sunlight, and air, and if they don't have water, then they can't make it. (Make what?) Sugar. They need sugar for energy for the cells.

Thus, at the end of the year, Brenda readily explains this phenomenon by drawing on knowledge about photosynthesis and the way that plants make their own food out of air, water, and sunlight. This was knowledge Brenda had developed across the year. Although photosynthesis was studied in the fall, Brenda easily accesses this idea in explaining the drought phenomena. Although this issue about the drought had not been explicitly discussed during or after the photosynthesis unit, Brenda was not intimidated by the question and she did not resort to more typical fifth grader kinds of explanations of the phenomenon (such as, "because they need water to live").

Another question that challenged students to use their knowledge about photosynthesis was asked on both the pretest and the posttest for the photosynthesis unit. Note how on the posttest Brenda confidently uses knowledge about photosynthesis and about food storage in the seed's cotyledon that she apparently did not have at the time of the pretest:

> Question: A man wanted to have an early garden. He planted some tomato seeds in small boxes. He kept the boxes in a closet where it was warm and dark. He watered them whenever the soil started to get dry. There was plenty of air in the closet. What do you think happened to the seeds? Why would this happen?
>
> Brenda's pretest response (10/10/88): I'm not sure if the plant would come up and die or if sun light comes up trought dirt or not. I can't answer [why] because of the question above.
>
> Brenda's posttest response (12/1/88): They would come up but then they wold die At first the condlyen would give it food but whene the [they] came up and had leaves they ate all the codlyen up. And then it was time for them to make food on there one

> [own]. But there was no sun to mix with air and water so they could not make food and died.

An interesting aspect of Brenda's ability to use the idea of photosynthesis was her changing and deepening understanding about photosynthesis across the year. In particular, she gradually developed understandings of the complexities of photosynthesis that helped her explain why fertilizers and minerals are not considered energy-containing food for the plants (an idea that she firmly held at the beginning of the plant study). The set of responses below illustrate how she gradually moved from using the idea that fertilizer is food for plants to using the idea that fertilizers are needed by plants (for things like protein synthesis and cell building) but they are not the energy-containing food for the plants:

DATE	QUESTIONS	BRENDA'S RESPONSES
10/10/88	Pretest: Describe what food is for plants.	Fertalizer is for plants it is powtery and you add it to water and pour it on the plant
10/26/88	Text: Plant food or fertilizer that you buy at the store contains minerals help the plant grow better, but it does not supply plants with energy. Is "plant food" really food by the scientific definition?	Yes. Why would it say plant food. I think that there is energy in the food.
10/26/88	Quiz: Do you think the cotyledon will be the only source of food for a bean seed as it grows into a full size plant? Explain your reasons for your answer.	No. I think the cotyledon will fall off and you could give it plant food.
10/27/88	Could a plant stay alive and grow if the only food it got was the fertilizer or minerals from the soil?	Yes. Becuse fertilizer is food and so is minerals.
	------------------Shift in perspective------------------ A memorized response?	
11/88	Would it help the bean plants in the dark stay alive if you put fertilizer on them? Why or why not?	No fertilizer does not have any engry

11/14/88	Ballot Quiz: Write "yes" or "no" or "I don't know" to tell whether each of the following is or is not food for plants. Then give a reason for each answer.	water yes--I helps the plant make food fertilizer no--you told us it wasn't I don't rember why soil/dirt no--it is just there for somethin plant food no--the same as fertilizer cotyledon yes/no--When the plant is just a baby it gets food from it. But when its' bigger it doesn't air yes, it helps it make food something the plant makes yes- -that's its food sun yes-it helps it make food

------------------------------------Shift in perspective------------------------------------

A satisfying reason?

4/24/89	Journal Entry: Write about your day as an oxygen atom.	Journal Entry: My Life as a oxygen atom! Frist I was part H2O and CO2 then I had my amzing day! I was just floting in the water when I somehow got into a plant and I got chaned into suger I tried my best to get out but it was no use, Then I was really surprized when I was compined wind [with] Nitrogen and Phosphorous and guess what I was chened [changed] into Protein. I thought this was fun a fisrt but I just want to be O2 agin. Then I was partly bitten of into a fish och that hert [ouch! That hurt] then the fish a the nev [had the nerve] to die with part of me still in him can you imgan! Well I didn't have the slidest idea how to get out The bacteria where coming in after me and my fried [friend] CO2 well luckly I got out but I nverer saw the rest of me agin. And to think all this happend because I swim into a plat [plant]. What a day!
5/8/89	Plants grow better if they get minerals and fertilizers from the soil. Why do plants need minerals from the soil?	Plants need minerls from the soil to help them change suger into proteins. The soil has no food energy.
5/25/89	Ecosystems posttest: A nitrogen atom is in the soil of our aquarium. Tell a story that shows how this nitrogen atom (a mineral) can move in a cycle in the aquarium ecosystem.	I was just a little nitrogen atom in the sane [sand] of a fish tank no herting a thing when I was sucked up in a roots of a plant and changead into protien then the plant died and got decomposed and I went back into the soil.

Brenda was asked numerous questions in interviews and in science class that provided opportunities for her to use the ideas about photosynthesis and plants' making of food. Below are a sampling of some of these questions. Brenda's responses consistently reflect her ability to use photosynthesis to explain the situations. They also illustrate how her understandings of the similarities and differences between plants and humans deepened across the year. After the related units on photosynthesis and on body systems/cell respiration, she had developed a clear understanding that plants can use carbon dioxide in a way that people cannot (to make food) and that plants, just like people, use oxygen to combine with food in the cells to release food energy for use by the organism (cell respiration).

DATE	QUESTIONS	BRENDA'S RESPONSES
During the Photosynthesis Unit:		
	Some large and some small seeds were caught in an animal's fur. The animal went into a dark, abandoned mine. There was no light in the mine. The seeds fell out of the animal's fur. Plants began to grow in the moist mine. Do you think the plants will survive? Why?	No. becuse it needs light to make food.
	Can the cells in the seeds, fruits, and vegetables that we looked at make food? Why or why not?	no. it has know way to get sunlight and it is not green so it as [has] know clorafel
At the Beginning of the Human Body Systems Unit:		
11/30/88	HUMAN BODY SYSTEMS PRETEST:	
	Do people need air to stay alive? Explain why or why not.	We need air to breath.
	Do plants need air to stay alive? Explain why or why not.	So they can make thire food.
At the End of the Human Body Systems Unit:		
3/3/89	HUMAN BODY SYSTEMS POSTTEST:	
	Do people need air to stay alive? Explain why or why not.	Yes. We need air to mix once in the cells with food to relce [release] engry but we cannot use carbiox dixoced.
	Do plants need air to stay alive? Explain why or why not.	Yes. They need air to stay alive because they need carbiox dicoxide to make their food they need oxgeyn to relase the energy in its cells.
	Circle any of the following living things that need to breathe in oxygen. Explain your choices.	humans, frog, bean plant, cow, oak tree, cat gerbil. Every living thing need oxgeny to realse engry. Without it nobody could live.

During the Ecoysystems Unit:

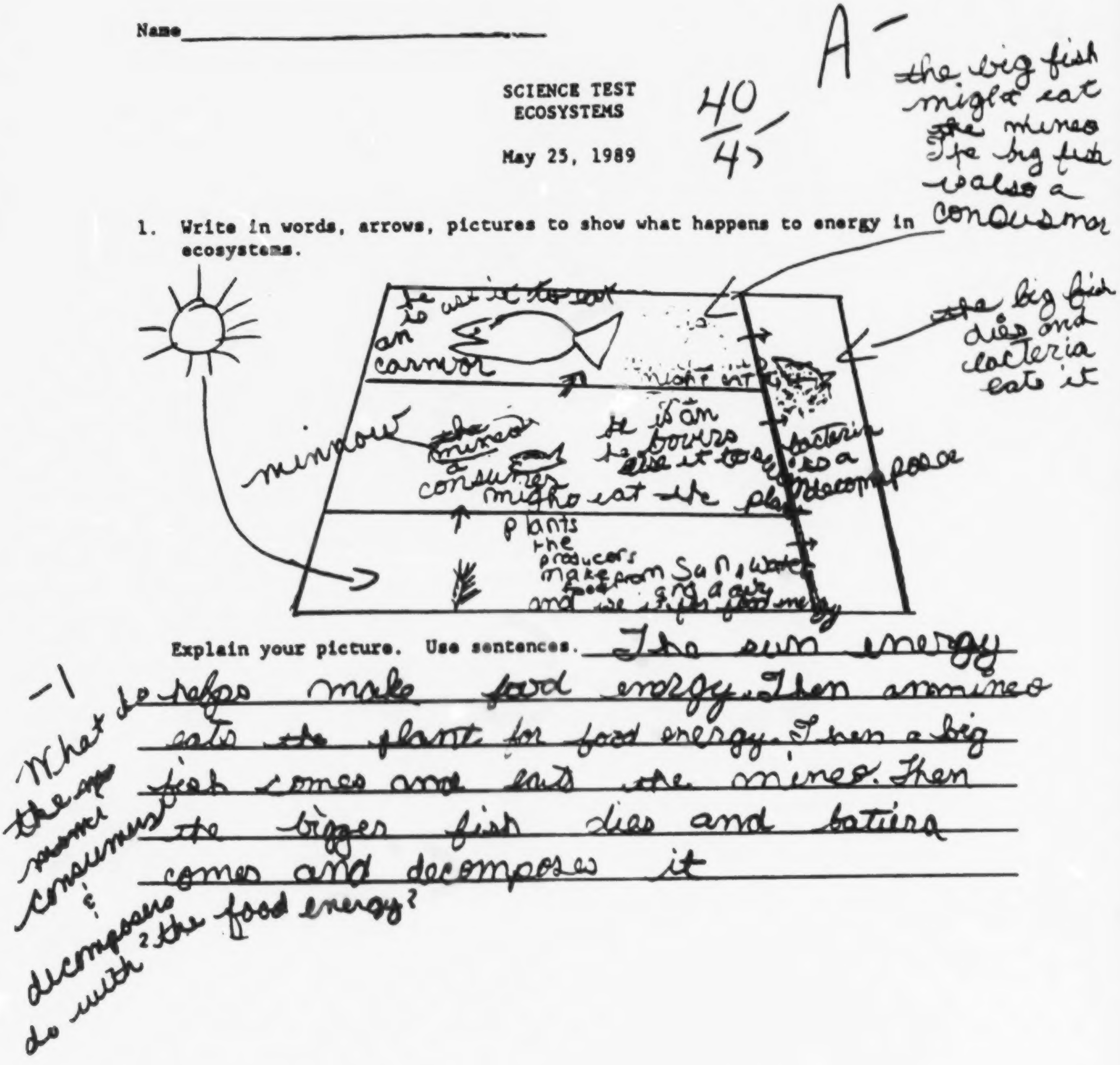
3/89	One year when Mr. Jones' fishpond froze over and was covered with snow, the water plants and fish died. The next winter Mr. Jones and his son Dick removed the snow from the ice-covered pond after each storm. When the ice thawed in the spring, they found that both the plants and the fish were still alive. Explain how the snow removal might have allowed the organisms to survive.	It might get to cold in the water for the fish and plants. or there was not enough air being aloed to get to the water the snow covering it. The sun light could also get through the water for the plants.
4/10/89	ECOSYSTEMS UNIT: Suppose some seeds got stuck in the fur of a rabbit. The rabbit went into the cave. The seeds fell off the rabbit and fell into the wet soil on the floor of the cave. Do you predict the seeds would grow? Explain.	No. No sun would be able to come in eather [neither] would rian water so the plants would not be able to do ainy photophisises.
5/8/89	Plants grow better if they get minerals and fertilizers from the soil. Why do plants need minerals from the soil?	Plants need minerls from the soil to help them change sugar into proteins. The soil has not food energy.

After the Ecosystems Unit:

5/25/89	Ecosystems Posttest: Write in words, arrows, pictures to show what happens to energy in ecosystems. Explain your picture.	The sun energy helps make food energy. Then a mineo [minnow] eats the plant for food energy. Then a big fish come and eats the mineo. Then the bigger fish dies and batiera comes and decomposes it. (See Figure 3)

During End of the Year Interview:

5/30/89	Would it cause any problems if we removed all the plants in the world?	Yeah, it would cause problems because animals eat the plants and the herbivores eat the plants and the carnivores eat the herbivores. And if the plants die then the herbivores eventually die and the carnivores eventually die and we couldn't eat any animals and we couldn't eat any like vegetables or any plants. They [animals and people] can't do photosynthesis.
5/30/89	Where did the energy in this candy bar come from?	Well, are there peanuts in this? Well, the peanuts have energy. Well, the peanut plant made and stored some of the sugar in the peanuts. And then there's chocolate in there which came from cocao [cacao], or whatever it's called, the plant, so so that's from a plant so that has energy. And then caramel...the sugar [in caramel] came from the plant.



Name________________________

A-

SCIENCE TEST
ECOSYSTEMS

40/45

May 25, 1989

the big fish might eat the mineo The big fish is also a consusmor

1. Write in words, arrows, pictures to show what happens to energy in ecosystems.

he is use it to eat
an carnvor
minnow
~~the~~ mineo a consumer might eat the plant
he is an bowers he else it to see
bacteria is a decompose
plants the producers make food from sun, water and a air and we it for food energy
the big fish dies and bacteria eats it

Explain your picture. Use sentences. The sun energy helps make food energy. Then a mineo eats the plant for food energy. Then a big fish comes and eats the mineo. Then the bigger fish dies and batiera comes and decomposes it

-1

What do the consumers & decomposers do with the food energy?

Figure 3. 5/25/89 Ecosystems Posttest: Brenda's drawing of a food chain.

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5/30/89	What kinds of talking goes on in science class this year?	We have discussions like little arguments of what some people think one thing and some people think another thing. Like we did a paper and we saw it and some people thought that the fish would die if there was ice in the pond all winter and some people thought they wouldn't die.
	What do you think about that question?	If it didn't have any snow over it and the sunlight could get through to help make food energy for the plants, yeah, it could live.
5/30/89	Why is it important to know about photosynthesis?	So you can know how a plant makes its food. So you know that the water you are giving the plant water in your house and you know what it's doing with that water.

At the end of the year, I also was able to interview Brenda's parents. I hoped to get some insights from interviews with parents about ways in which students were or were not using their science knowledge outside of school. Brenda's mother and father were most struck by the ways in which Brenda was using her knowledge to ask questions (which I'll have more to say about in the next section). They also were amazed at the ease with which their fifth grader tackled what seemed to them to be quite difficult science application questions. Brenda's dad commented, "The ecosystem unit had some really sophisticated kinds of ideas in it and she seemed to be able to do it. I was really impressed with her ability to sit down and answer those three pages of essay questions in an evening." Similar stories from parents confirmed that students were thinking and using science concepts at home: Cherille was gardening with her mom and looked up at a huge oak tree in their yard and wondered aloud how much water such a huge tree would need to do photosynthesis in all its leaves. Kurt was watching a television advertisement for some kind of aspirin and challenged the announced speed with which this drug would take effect--it seemed to him that it would take a lot longer to get all the way through the digestive system and into the bloodstream and to the cells.

The ways in which Brenda and her classmates were able to use the main concepts we studied were exciting. These fifth graders convinced me that students can think much more deeply about complex ideas in science than we have given them a chance to do--and much more deeply than students I had taught and studied in the past. However, I think much more is possible for fifth graders than I was able to help this group of students accomplish. Thus, while their abilities to use their knowledge stand out as being different from traditional classrooms, I think this study only scratched the surface of what students this age may be capable of doing.

Brenda's Understanding of the Nature of Science and Scientific Ways of Knowing: A Paradox

Brenda learned that science is a way that she could make sense of the world around her. As shown above, Brenda was able to understand in quite sophisticated ways connections among concepts such as photosynthesis, cell respiration, decomposition, ecosystems, chemical change, food, energy, and so forth. And she was able to use new understandings to make predictions and to explain real-world phenomena. But what kinds of knowledge and dispositions toward scientific thinking and ways of knowing did she develop?

Analysis of Brenda's understanding and appreciation of the nature of science, scientific thinking, and knowledge growth in science reveals a paradox: Brenda views her personal science learning as a process of change and growth in which new questions arise as new knowledge is acquired, and in which debate and argument are useful learning tools. But Brenda's view of science outside the classroom is disturbingly static--the questions she is asking can all be answered by scientists. She sees a lot of questioning, confusion, change, and uncertainty in her own developing science knowledge while characterizing scientific knowledge as certain, stable, "right," and complete. Brenda, like most of her classmates, typically had difficulty connecting activities and norms of our science classroom with activities and norms of scientific communities. I would argue that it is possible for fifth graders to develop much richer understandings of the nature of science, but that they need more explicit instructional support in reflecting on the connections between their classroom experiences and the ways in which scientists operate in scientific communities.

In this section I first describe the ways in which Brenda, like many of her classmates, developed some important understandings and appreciations of scientific ways of knowing. This "good news" is then followed by the "bad news," a description of some important misperceptions Brenda holds about science.

The good news. An important understanding that Brenda developed is that in science you can ask questions you are wondering about and get personally meaningful answers to these questions through a variety of strategies for gathering evidence. It is clear that Brenda viewed science as addressing her *own* questions, not just questions laid out by the teacher or the textbook. And Brenda, like *all* of her classmates, had interesting questions to raise. The classroom environment invited, encouraged, and rewarded question asking, and Brenda raised many questions. Many of these she recorded in our classroom Question Notebook, a place where good questions were saved and often revisited:

10/24/88	If the plants don't use the soil, why do they need it?
11/15/88	How come the plants need minrls
11/15/88	How come a tree has toths [two] colors in it?
11/16/88	What do they do to a tree when they tap it for maple surger?
11/22/88	How come when you eat somthing really salty you get [thirsty]?
12/12/88	What does poisen do to your body?
12/14/88	Why do people need cells in there body?
1/89	What makes a heart beat?
2/8/89	Why when a person has a cold why does there nose plug up and you can't breath?
2/23/89	Why do trees plants need the air we breath out?
4/10/89	Why does mold smell in are jars and not that bad on bread?
4/24/89	Why does the sanil [snail] in our tank eat the dead fish?

She used her Science Log Book (a science journal) as another place to wonder, to conjecture, to make predictions, to raise questions, and to reflect on her appreciation of her new learning:

9/1/88 This summer I noticed beach hoppers in Calaifoma. I wondered where did thay come from
I noticed hot air bloons and I wondered: How do they say up when gavdy [gravity] is pulling verything down.
I noticed: The under water tunel to caneda from Deriota [Detroit] I wondered: It goes under the water so how they gett it under the river

9/27/88 I don't think this is a good experement becaue I dont undstand whey they shood only water 2 of them I think they shood not water all of them it's not a fair experiment if you olny water 2 of them

10/19/88 I think the grass seeds do not have embryos and cotyledons becaus they are not beens they [are] seeds

10/24/88 I though it was interesting that a peanut has a embryo and a codelyolun because I didn't know that before

11/16/88 Do flowers make food like plants
Where they tap the trees for maple surpet does it hurt the tree

[I thought it was interesting] that they [plants] have tubes kind of like viens that carey the suger from place to place

2/1/89 I wondered Why the frog has three livers. Why were the [they] begger in porshon [proportion] to the frog's body than to ours

In interview situations she also reflected that she was genuinely intrigued and wondering about things she was studying in science:

> KR: Is there anything about plants that you wish you knew more about?
>
> B: I kind of always wondered how this one [the cactus], what's inside of it and how it stores the water, the cactus.

Because a unit was "finished" did not mean that all of Brenda's questions were answered. Although she felt like she had learned a lot, she was comfortable recognizing that this new knowledge just led to more questions and unknowns. And she saw that her questions were valued in science class. Her persistent asking about the function of fertilizers in plants, for example, eventually encouraged me to attempt an in-depth study of the cycling of matter (including minerals in fertilizers) in ecosystems during the spring. And our study of the human body allowed Brenda's questions about her father's heart attack to become part of our curriculum. Science class became a place for her to raise these questions about heart attacks; support at home enabled her to pursue some of these questions outside of school. She then presented her findings about heart disease and heart surgery to the class.

On another occasion, her interest in doing a frog dissection during the human body unit (an interest enthusiastically shared by many of her classmates) led to a detour in the planned curriculum to encourage debate and thought about the use of animals in research. Brenda thoughtfully questioned and listened to an MSU scientist discuss animal use in his research, concerns about animal rights, and alternatives to animal testing. In the end, Brenda had many new questions about animal dissection, but she was rewarded for her questions by being given the choice to participate in a frog dissection. She and her classmates wrote up their research proposal, justified the use of animals in this research, and conducted the dissection with a seriousness of purpose that I had never seen in the dissections I had done in my earlier teaching.

Brenda clearly viewed her own science learning and sense making as a social rather than a private event and as a process of change rather than as an accumulating pile of knowledge. She reflected thoughtfully not just on new ideas she had learned but on changes in her thinking and ways in which social interactions in the classroom--especially debates and "arguments"--enabled these changes:

> 12/1/88 Photosynthesis Posttest (Q=Question):
>
> Q: Have your ideas about how plants get their food changed since the beginning of the unit? Explain.
>
> B: Yes befor I thought that water was food for plants but know I know that water is just part of the proses.
>
> 5/30/88 Interview:
>
> KR: Are there some things about this topic [a topic you understood really well] that you did not know before this year? How have your ideas changed after studying about this topic?

B: [photosynthesis] Because before I didn't know how a plant even got food. I just thought it used water for its food. Now I know about all the chemical changes that happen in the plant to make sugar.

KR: Any other things?

B: Yeah, I didn't know anything about how plants got their food at all. I didn't really care either; I just thought I gave the plants in my room water and I thought that they just lived without food.

* * * * * *

KR: What kinds of talking goes on in science class?

B: We have discussions like little arguments of what some people think one thing and other people think another thing. Like we did a paper [a worksheet that presented the ice-over-the-pond problem] and we saw it and some people thought that the fish would die if there was ice over the pond all winter and some people thought they wouldn't die and things like that.

KR: What do you think about that?

B: If it didn't have any snow over it and the sunlight could get through to help make energy for the plants, yeah, it could live.

KR: Is it a good thing or a bad thing or both to argue like that?

B: It's good to argue so both people can know and have an understanding for both things and know what both people think.

KR: Is the talking helpful?

B: When we have partners, we can talk to our partner about what we think. That's helpful because if we don't have an answer to a question or we don't understand, our partners can help us out because maybe they understand it.

* * * * * *

B: If you want to say something, if you have an opinion or you want to make a guess at something you can raise your hand and just ask it.

KR: Who asks questions?

B: You [the teacher] could ask questions to us to see if we can figure it out. We could ask questions to you.

KR: Who asks questions more, the teacher or the students?

B: Students ask questions all the time if they don't understand something.

KR: Do you ask a lot of questions?

B: I think I do sometimes.

Scientists use models as tools for thinking and problem solving. Like scientists, Brenda found models and visual representations to be useful in her own learning:

> KR: What things helped you understand that so well?
>
> B: Discussion in class and those little plays that we did with the different cards. Those helped me out. They helped me learn the processes that it [the plant] went through to get it [food].

Models she used effectively were often drawings. On 1/24/89, for example, she was asked to draw or write about how she imagined food could travel through semipermeable cells to get in and out of the bloodstream. Unlike many of her classmates Brenda confidently drew a picture to represent her thinking. In the center of Brenda's "three dimenshal" picture (see Figure 4) are food (represented by tiny dots) and blood cells traveling in a vein that is itself made up of tightly packed cells. She shows some of the food particles moving into these surrounding cells. On a quiz in April she again shows her ability to use pictures as models to represent her thinking. On this quiz, her picture represents a central idea about energy ("everything in this ecosystem gets food energy") that is not captured in her written explanation that accompanies the picture (Figure 5):

Science Quiz, 4/89

> Brenda's explanation of the picture: Plants get there energy from the sun warter and air the prosesses is called Photosynthesis then an herbivore (rabbit) eats the plant then a carnivore (owl) eats the rabbit the hole thing is a for chain witch is in the Ecosystem.

Sometimes the models she found particularly powerful were ones she called "skits," a type of model that may at first seem unscientific but which for Brenda served the same functions as more scientific models, helping her put ideas together and imagine them in ways that made them sensible to her. Notice, for example, how she was able to talk about an activity in which her teacher came in dressed up as a plant in terms of a model:

> B: You were a model of a plant. [You were a good model] because you were green. You had potatoes growing on your legs. Because if you are a potato plant, you usually have potatoes to store your extra food. And those little tights that you were wearing, they had little stripes on them, they look like roots kind of.
>
> KR: In what ways wasn't I a good model?

B: You were too big. You had eyes and a nose and body parts that a plant doesn't have and you talked. Did I mention that you were too tall? And you didn't have any leaves.

On other occasions students had created skits to model how plants get their food and to show what happens to food and oxygen once taken into the human body. In creating this latter skit, students first wrote about events in the body from the perspective of the "part" they were assigned (oxygen, food, cell, small intestines, heart, etc.). Brenda imagined her part as the small intestine:

> Ho Ho he [here] it comes I can feel it coming in goosh. I'm the small intestine my job is to break down the food and sent it to the cells. But right now I jiggle it all up and digest it. Boy I can bearly reach it hmt hmt they we go, I've got it. Right now (becaus the food Is small enough) I've got to grab it and sent it to the cells.

Brenda also learned that scientific knowledge can enable people, including herself, to both appreciate the environment in new ways and to act on that knowledge. In a year-end study of a particular ecosystem--rainforests--students studied the diversity of species and adaptations of rainforest organisms, used their knowledge of photosynthesis and cell respiration to predict the impact on the atmosphere of rainforest destruction, considered rainforest food chains, and explored why rainforest soils are so poor in fertilizers. The study provided a context not only for using concepts studied across the year (see Table 1) but also for exploring the ways different kinds of rainforest scientists work, the impact of human actions on our environment, an appreciation and concern for the beauty of this diverse ecosystem, and the interconnectedness of all life on earth. This study helped Brenda see science as providing knowledge that can lead to action:

5/25/89 Ecosystems posttest

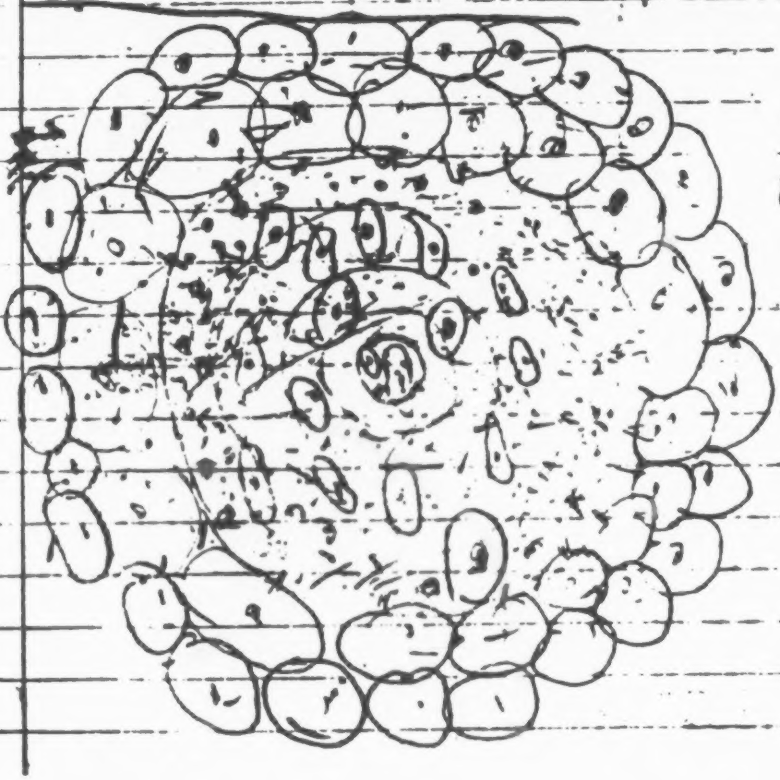
Q: Do you think rainforests should be saved from destruction? Pretend you are writing a letter to the editor and readers of the Lansing State Journal about the rainforests. Write down how you would explain your point of view.

B: Dear Editor and readers of the Lansing State Journal, The rainforest are just too important to cut down and destory. Senicetist predict in 40 years there will be no rainforest left in the would. Well everbody should care becoue without rainforests are climates will change. It will get hoter and hoter. So rember to save the rain forests and save the would.

72

January 24, 1989

Cell membranes,
blood vessel walls, and
small intestine wall
are all semi-permeble
like a screen. Some things
can get through them
and some things cannot
One important thing that can
get through these wall is
food enery. medicie poisen.



Three dimensbal
blood

Figure 4. Brenda's drawing of how food gets in and out of the bloodstream.

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Name______________________________

A- Good!

SCIENCE QUIZ

1. Arrange the following words in a word picture or a diagram in a way that makes sense. Use arrows where needed and label the arrows to tell what they mean.

ecosystem
light energy
herbivore (plant-eater)
producer
photosynthesis

food chain
carnivore (animal-eater)
consumer
food energy

An Ecosystem

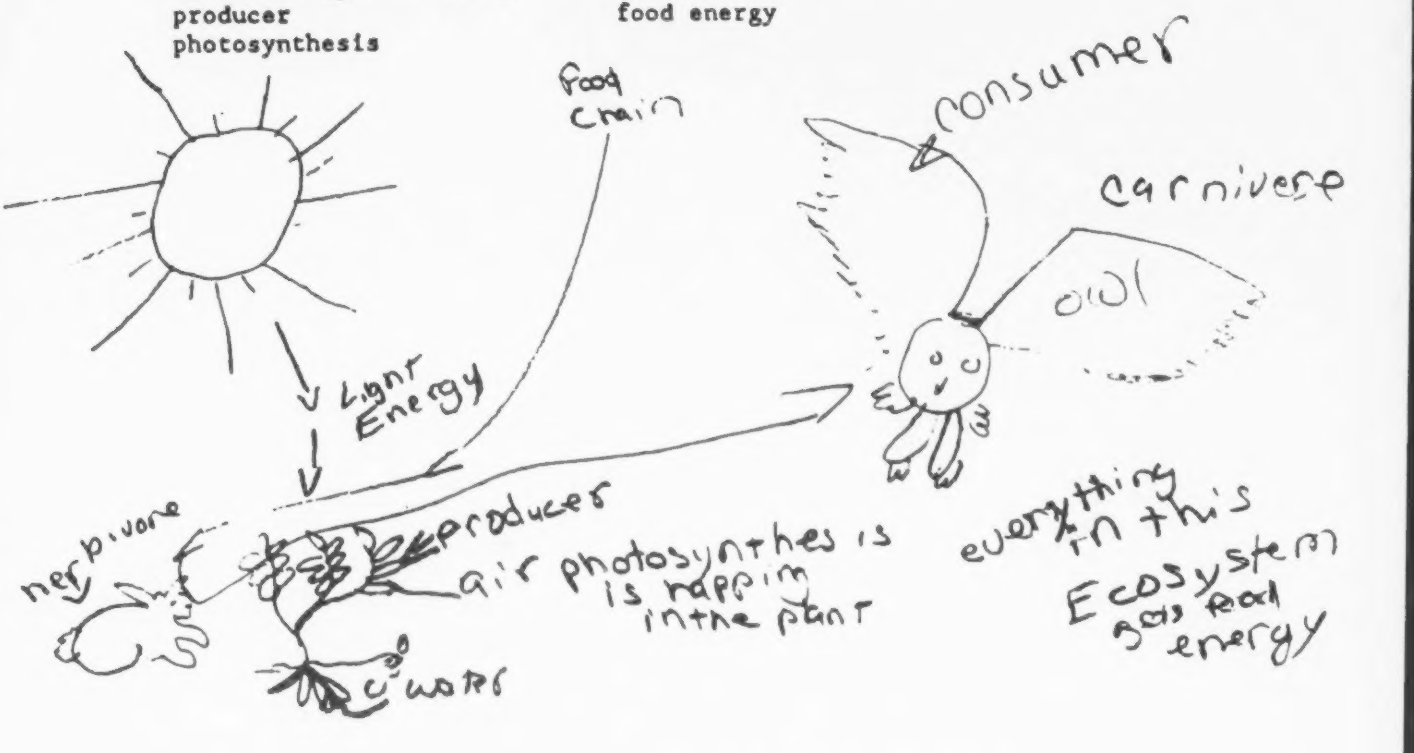
Food Chain
consumer
carnivere
owl
Light Energy
producer
herpivore
air
photosynthes is is happin inthe plant
water
everything in this Ecosystem gas food energy

Figure 5. Science quiz 4/89.

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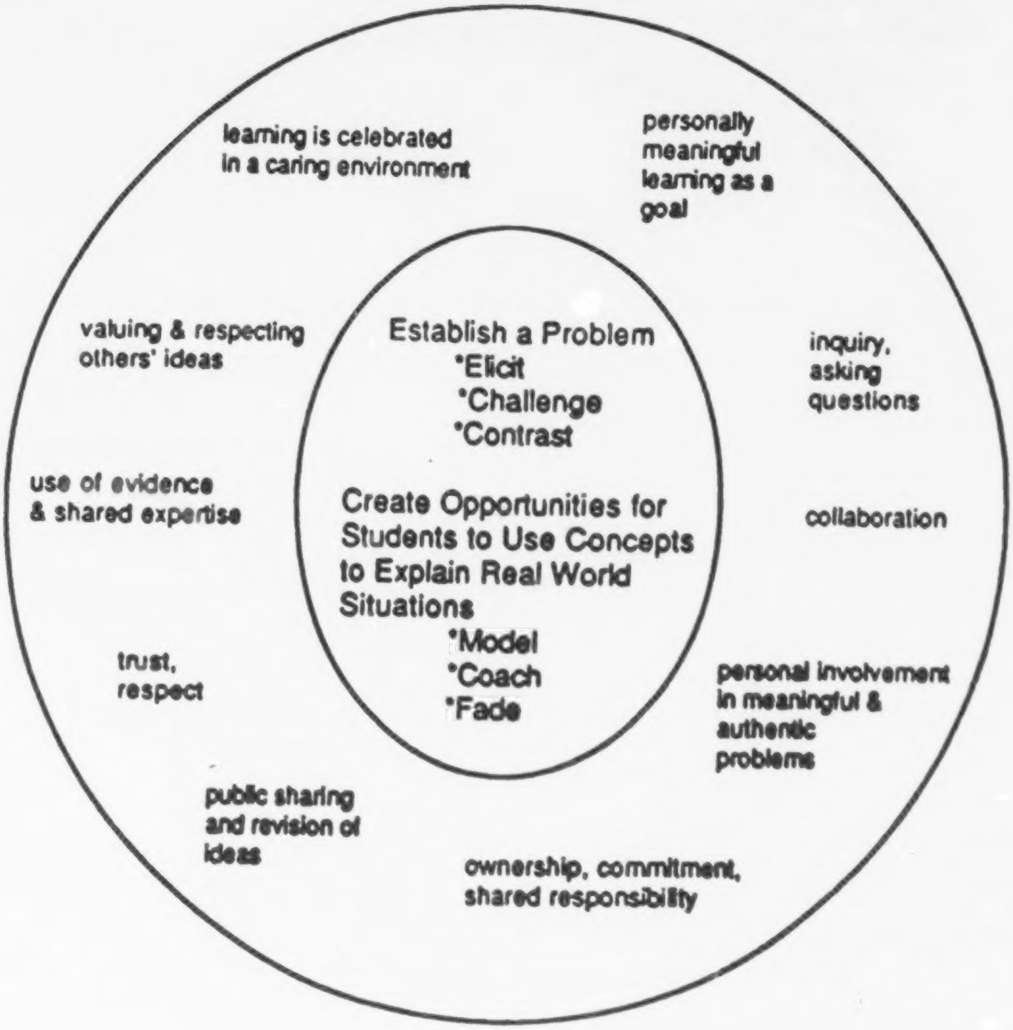
learning is celebrated in a caring environment
personally meaningful learning as a goal
valuing & respecting others' ideas
Establish a Problem
*Elicit
*Challenge
*Contrast
inquiry, asking questions
use of evidence & shared expertise
Create Opportunities for Students to Use Concepts to Explain Real World Situations
*Model
*Coach
*Fade
collaboration
trust, respect
personal involvement in meaningful & authentic problems
public sharing and revision of ideas
ownership, commitment, shared responsibility

Figure 9. A conceptual change science learning community.

Table 2

A Learning Setting vs. a Work Setting: Creating a Conceptual Change Learning Community

A CONCEPTUAL CHANGE SCIENCE LEARNING COMMUNITY	A WORK-ORIENTED CLASSROOM SETTING
*Sense making and learning as the goal	*Getting the work done as the goal; getting facts learned or activities and projects completed
*Personal, emotional involvement in meaningful and authentic problem situations	*Depersonalized, unemotional relationship with work, getting the products made
*Ownership and commitment by each person; responsibility shared	*Teacher as executive in charge of everything
*Active inquiry and question asking are valued and encouraged	*Getting the right answer is valued and encouraged
*Expertise comes from everyone, is shared; learning is a collaborative process	*Expertise comes from the teacher and learning is a private activity
*Everyone's ideas are valued and respected as useful in the learning process; diversity is celebrated in a caring environment	*Workers need to keep quiet and busy; diversity is a problem for quality control and efficiency
*Good learners listen to each other	*Good workers listen to the teacher
*Public sharing and revising (working out) of ideas	*Only complete, polished final products are shared
*Evidence, not authority, is used to construct new knowledge and judge merits of ideas	*Knowledge comes wrapped in neat packages that are delivered from teacher or text to student; all packages are to be appreciated and not questioned
*Each learner starts and finishes in a unique place; learning as a process of conceptual change	*All workers create the same product or else are failures; learning as a "you have it or you don't" phenomena

NOTE: The metaphor of a learning vs. a work setting for thinking about classrooms was adapted from Hermine H. Marshall (1990) in "Beyond the Workplace Metaphor: The Classroom as a Learning Setting" in Theory Into Practice, 29, 94-101.

5/30/89 Interview

Q: What is science all about? Why do people study science?

B: So they can learn about what's happening in the world. So we can study what's happening in the world so they can know what things to expect like if the rainforests are all cut down so they know what to expect, how things are working.

Q: What would you want all the students to remember about ecosystems?

B: Maybe all the destruction that's going on in the ecosystems...how it can affect us.

Q: Why do you think it is important for people to know about ecosystems and how destruction of ecosystems can affect us?

B: So we can maybe when we are adults or something, to help prevent destruction of rainforests and ecosystems.

Thus Brenda--a student who would have dutifully and quietly memorized facts and completed assignments in a traditional, text-based science classroom while being disengaged intellectually--was in this context an active inquirer, a sense-maker, a creator of models, a student who was not satisfied with partial explanations. It is exciting to see her use these scientific ways of knowing. But her understandings and images of science and scientists were also limited in important ways.

The bad news. While Brenda felt comfortable raising questions and exploring them by constructing models, debating ideas, doing experiments, she maintained a view that science and scientists have the answers. She did not appear to transfer the idea of inquiry, debate, argument, and conjecturing from our classroom learning situation to the world of science. In talking about science in our classroom, for example, notice how often she refers to "the answer" or being "right" (emphasis added to highlight these occasions):

5/30/89 Interview

KR: What other things go on in class discussions?

B: Somebody saying the real answer and then trying to figure out things. When we were learning about photosynthesis or however you say it, people were trying to figure out how that really, how plants got their food and how its cotyledons or whatever got their food before they sprouted out.

B: You could be talking. You might talk about that you want us to do something in the log books, or you might help us, you might start a discussion going about something and talking and maybe tell us the answer so we can figure it out.

B: [It's important to ask questions] so you can know the answer to something and so you can know the answer to it or somebody can give you the answer.

B: [The Question Book] it's when you don't want to tell us the answer right now and she wants us to keep our guess and we go write it down in the Question Book so we can remember it, I guess if when we come back to it.

B: Sometimes I get frustrated because I want to know the answer right away and sometimes it's OK because I don't need to know the answer right away.

B: [About writing in science class] we write a lot. We write about things we are learning and like the little story of the cell and the atom or something. On tests we write the real answer and in the log book we can write what we think even if it's not right. [That helps in our learning] because so we will have what we think so we can learn how we, so that we can learn to make guesses instead of always having to find out the real answer.

Q: Could it be that both people are right?

B: Yeah, in a way. That they both are right because they expressed their opinion and they probably made a good guess even though it's not right.

Although Brenda recognizes that there are still things she does not know about plants, she assumes that she will learn about those things "in high school or junior high." She does not mention that some of the things she doesn't know may not be known (or may not be knowable) by scientists. She seems to have an unquestioning faith in scientists' "answers."

Brenda's notion of a "right answer" existing out there somewhere meant she did not have to be critical of anyone else's ideas or different sources of evidence--an activity encouraged in class that seemed to be uncomfortable for her. She was reluctant to view different positions or perspectives as representing anything more than different good ideas or guesses. In this sense she holds the notion that everybody's ideas are as good as everyone else's--that everybody has good guesses and opinions even when they do not match the right answer.

During a class discussion at the beginning of the photosynthesis unit, a classmate and good friend challenged Brenda's idea that sun does not have energy. In a very caring response, Brenda tried to smooth over or "fix" this disagreement:: "I said, um, I asked if sun has energy in it." Her comments at the end of the year suggest to me that although she now says arguments are a good thing, she appears to be struggling to convince herself and the interviewer that arguing can be a good thing in science:

KR: Is it a good thing or a bad thing or both to argue like that?

B: It's good to argue so both people can know and have an understanding for both things and know what both people think.

KR: Could it be that both people are right?

B: Yeah, in a way. That they both are right because they expressed their opinion and they probably made a good guess even though it's not right.

Although Brenda says it is a good thing to debate and argue, she smoothes over the disagreement part of arguing and focuses instead on "expressing their opinion" and making a "good guess." Her resolution of the problem is contradictory: "They both are right" even though their opinions are "not right."

As I analyze there interview responses, I see Brenda attempting to reconcile her personal beliefs and values about "being nice" with her teacher's clear valuing of debate and argument. Brenda apparently felt comfortable with the nature and flavor of these classroom arguments and even recognized them as useful to her learning. But she did not seem to understand why they were valued in science. She may have been wondering like one of her classmates, Annie, who blurted out during a class discussion one day: "Ms. Roth, do you like arguing or something?" (classroom transcript, 4/5/89). She constructed her own resolution of what for her was a paradox. My hunch now is that students like Brenda--and I think there are many like her--need much more explicit support in making sense of a community in which a certain kind of debate and argument is valued.

Many students, in fact, may feel uncomfortable and turned off by aspects of scientific communities that feel to them hostile, combative, and competitive instead of communities that are cooperative, friendly, supportive. The community in our classroom posed a contradiction for Brenda--it felt cooperative, supportive, and friendly but at the same time there was a clear valuing of debate and argument. Such a contradiction was not easy for students like Brenda to resolve on their own. As their teacher, I assumed that my modeling of debate and argument was sufficient to enable students to internalize that these were important norms and ways of being in scientific communities--both within and outside our classroom. I was wrong. It now seems to me that it is critical that science teachers explicitly teach students how to participate in the special discourse of science communities--ways of thinking, talking, and acting that include particular rules of evidence and modes of argument. Traditional outsiders to science--girls, like Brenda, for example--especially need help in learning the nature and value of scientific discourse. (Michaels & O'Connor, 1990).

Is it possible for fifth graders to view science itself as changing, as not having all the answers? Is it possible for fifth graders to develop and be comfortable with scientific modes of argument? My experiences with Brenda and her classmates suggest to me that it is not enough to engage students in scientific debates or to model question asking and uncertainty. Such models stand in such stark contrast with students' experiences in school (where teachers know all the answers) and in society (young ladies should always be nice and polite). Students may need support in making sense of a community in which these norms are challenged.

What's Different About Brenda's Understanding of Science?

The understandings that Brenda and her classmates developed about science and about particular science concepts are striking to me. They stand in contrast both with my memories of my former seventh-grade students and with the careful research studies of students in fifth- and seventh-grade classes conducted by Edward Smith, Charles Anderson, and myself (Anderson & Smith, 1983; Roth, 1986; Roth, Anderson, & Smith, 1987; Smith & Anderson, 1984). In contrast with typical student views of science, Brenda does not see science as a bunch of isolated facts and vocabulary words that are memorized and then quickly forgotten. Instead, she sees science as a set of big ideas (energy, food production vs. food consumption, cycling of matter, interconnectedness of living things, structures and functions, etc.) that can be connected to each other in a variety of ways. These are ideas that she can use flexibly and that become part of her way of thinking about the world around her. Remember how articulately she could talk about the concepts studied in fifth grade a year later. This sense of comfort with the concepts is strikingly different from what we are used to expecting from students--from what we are used to counting as understanding.

Secondly, her understanding of the usefulness of scientific knowledge and her willingness and disposition to puzzle through new situations, drawing from the conceptual knowledge she has developed, is different from what most students take away from their science studies. Her sense that ideas she has developed can help her figure out the world around her leads her to ask questions and to pursue them. Her willingness to change her ideas, to pursue questions with persistence until the evidence convinces her of a satisfying explanation, her understanding that science is all around us (not just in school)--these are characteristics of scientific thinking that we too rarely see in science students.

Because Brenda was not unusual among her classmates and because these fifth graders' understandings of science were so different from those of my earlier students, I became convinced that my new way of thinking about the kinds of understandings I wanted students to develop (Figure 1) and the conceptual change instructional framework I was using (Figure 6) to support students in developing these kinds of understandings were potentially powerful tools for guiding science teaching.

What's problematic about Brenda's understanding of science? The problems I saw in Brenda's learning provided insights that helped me examine the limits of the instructional framework and the goals for scientific understanding that guided my practice. These became areas of inquiry in my future teaching. My focus on helping Brenda understand in deep ways some important concepts in science enabled Brenda to believe that she could "really understand" science. But I had assumed that through this process of coming to understand some big ideas in science, students would internalize some important ideas about the nature of science and scientific inquiry and about ways of knowing in scientific communities. Brenda helped me see that such links were not easy for students to make on their own. Brenda was comfortable changing her ideas, debating ideas with classmates, asking questions, and feeling uncertain and confused. But she did not appreciate that these ways of being in our science classroom are also characteristic of scientific communities. Scientists were assumed to be much more expert, certain, and full of answers than our class. In her view, it is acceptable for students to learn, to ask questions, to get things wrong because they are students. Scientists are a different story.

Part 4: Teacher As Continuing Learner:

Learning About Science From Students And Colleagues

Learning from Brenda

After examining the limitations of Brenda's understanding of science, I found myself redefining again my understanding of what was most important for students to understand in science. Despite the wonderful sense of connectedness and usefulness in Brenda's scientific knowledge, I felt uncomfortable with her view of science. I want Brenda to know--in a conscious, metacognitive way--that her eagerness to ask questions, her willingness to tolerate ambiguity, confusion, and uncertainty, her persistence in refusing to accept explanations until the evidence really made sense to her, her openness to new ideas and change, her willingness to engage in debate, were important aspects of her scientific knowledge. These are the characteristics of scientific knowing that I want her to insist on using as she pursues her science studies and as she enters the adult world. I want her to know that these characteristics of scientific understanding are what enables her (and scientists) to dig deeply into questions and to develop better understandings of our world. These ways of knowing are important tools that I want her to carry into new situations and use even when the community she finds herself in is not encouraging her to use them. I do not want them to be ways of being that were useful in Dr. Roth's classroom but are then

A CONCEPTUAL CHANGE MODEL OF SCIENCE INSTRUCTION

ESTABLISHING A PROBLEM

*Eliciting Students' Ideas About a Natural Phenomenon

Students should see that other students have different ways of explaining the same phenomenon.

*Challenging Students' Ideas to Create Conceptual Conflict, Dissatisfaction

Engage students in thinking through whether there is evidence for their ideas and whether their ideas really make sense. For example, have students make predictions and then read or do a laboratory activity to find out if their predictions are correct or not. Encourage students to debate among themselves.

*Contrasting Students' Naive Explanations and Scientific Explanations

Explain and/or introduce new concepts in ways that are likely to make sense from the students' perspectives. Use a variety of different representations to explain new ideas (models, role playing, explanations, charts, diagrams, etc.). Compare/contrast students' ideas with scientific explanations.

UNDERSTANDING AND USING SCIENTIFIC CONCEPTS

Students need numerous opportunities to use new concepts to explain real world situations. A variety of activities and questions that engage students in using scientific concepts and in refining their understandings of these concepts will help students see the wide usefulness of the concepts. At first, students' misconceptions will persist as they answer these questions. The teacher, therefore, must play the role of "cognitive coach" (Collins, Brown, and Newman, 1987), helping students develop better strategies for comprehending concepts and explaining phenomena by:

a. modeling appropriate strategies
b. coaching students as they try to use the strategies
c. scaffolding the students' efforts to use the strategies
d. gradually fading the amount of teacher direction and guidance in constructing explanations for these questions.

Figure 6. A conceptual change model of science instruction.

CHARACTERISTICS OF SCIENTIFIC UNDERSTANDING

Kathleen Roth and Charles W. Anderson
July 1, 1990

I. CONNECTEDNESS OF KNOWLEDGE

A. Connections among science concepts and theories
B. Connections of science concepts and theories to prior knowledge or "real world" knowledge

II. USEFULNESS OF SCIENTIFIC KNOWLEDGE in activities that scientists and scientifically literate persons engage in:

A. Description of real-world systems or phenomena
B. Explanation of real-world systems or phenomena
C. Prediction of real-world systems or phenomena
D. Design of real-world systems or phenomena
E. Appreciation of wonders, beauties, complexities of natural world

III. NATURE OF SCIENCE AND SCIENTIFIC THINKING AND HABITS OF MIND

A. Disposition to reflect on scientific knowledge by:

1. Testing or justifying beliefs on empirical or theoretical grounds - looking for "best" sources of evidence
2. Criticizing arguments on theoretical or empirical grounds - having the disposition to critically evaluate arguments
3. Viewing knowledge as constantly changing, building, deepening over time - taking a historical and cultural perspective on the development of knowledge
4. Recognizing limits to knowledge - what is known, what is not known , what is knowable with current tools, techniques
5. Interacting with other people (through writing, discussion, argumentation) and valuing such interactions as an important part of the scientific community.

B. Disposition to construct new scientific knowledge by:

1. Asking appropriate questions
2. Developing solutions to problems using personal knowledge and reasoning, other resources, or empirical investigations
3. Interacting with other people (through writing, discussion, argumentation) to develop new understandings; viewing knowledge as cooperatively constructed within a scientific community.

Figure 7. Revised list of characteristics of scientific understandings, 1990.

forgotten just like all the memorized definitions of science vocabulary from earlier years in school science.

My study of Brenda helped me reconsider my definitions of scientific understanding. It has pushed me to recognize that in my enthusiasm for new insights about the central role of conceptual knowledge in scientific thinking and in my frustration with the dangers of viewing science as processes apart from concepts, I moved too far to the backburner important scientific habits of mind and dispositions that are also of central importance in scientific understanding. Working through these ideas with my colleague, Charles Anderson, I developed a new framework for thinking about critical features of scientific understanding that emphasizes the importance of habits of mind, represented in Figure 7 as habits of mind that enable one to reflect in certain ways about scientific knowledge and to construct scientific knowledge.

Because of my insights from Brenda, I now am representing science differently in my lessons. For example, I am being much more explicit about the connections between the ways of being in our science classroom and the norms and dispositions that are valued in scientific communities. As I am working with fifth graders I begin the year by briefly introducing the students to the nature of scientific work through a study of stereotypes of scientists. As part of this work we talk about aspects of scientific work that are central to what science is all about versus aspects of scientific work that are true only for some scientists and that do not represent the essential aspects of science (wear white lab coats, use microscopes, work in a lab, are men, are nerds). We keep a posted list of "Important Parts of Scientists' Work" that we continually refer to in our work and that we continually add to across the year. This year's emerging list (created as we reflect on our activities of the day) includes the following:

observing
predicting
asking questions and looking for answers
looking for evidence
estimating
comparing things

planning experiments
doing research
collaborating
talking
forming explanations--why? how?
disagreeing and agreeing with each other
forming hypotheses
using technology (tools) to help answer questions
reading
writing
using models
taking action
gathering and looking for data
thinking
working in communities; working together

The 1990-91 list was constructed at the beginning of the year based on an interview with a scientist and the teacher's synthesis of ideas. Thus, this list was more static and more teacher-constructed. It included the following:

discovering and describing our natural world
explaining the why's and how's of our world
asking and seeking answers to questions
solving problems, figuring things out
studying
observing carefully and keeping notes
talking to other scientists
writing about ideas, discoveries, and findings
reading journals to find out what other scientists are learning

These lists contrast with the lists we constructed about stereotypes about scientists:

wear white lab coats
use tools like microscopes, test tubes, beakers
are always experimenting
wear glasses
are men
have wild hair
are mad, crazy
like to be alone
work in a laboratory
work with poisons, explosives, chemicals
have beards
make monsters
are not old

The list serves as a reflection tool that helps us connect our daily work with scientific communities outside our school. We frequently end a lesson by reflecting on ways in which we've been scientists today. Other times, I interrupt a lesson to call students' attention to the ways we have been acting and how that compares with scientific communities. For example, I may comment on the way in which I saw people using their writing to work through ideas and how such writing often causes us to raise new questions. When we have had a good debate about the reasonableness of an explanation or the soundness of evidence, I call students' attention to the qualities of our discussion and the connection to scientific communities.

This curricular strand about the nature of scientific inquiry is not about the steps in the scientific method but focuses instead on the characteristics of scientific habits of mind--scientific discourse and ways of knowing. It is a strand that is woven into every unit of study across the school year (see Figure 8), not a unit that introduces students to the nature of science and then drops out of sight.

To help students become more aware of scientific ways of thinking and acting, I also look for opportunities to introduce students to particular scientists--either in person or through reading and videos--as we are exploring particular content ideas. Through these connections with real scientists I am always on the lookout for ways to challenge students to see multiple ways in which people can be scientists and also to see the universalities in scientific discourse: scientists' demand for evidence, their valuing of questions, their openness to change, their fascination with making sense, the collaborative nature of their work, and so forth. I use our visits with scientists as well as our everyday activities in science class to "talk about talk" explicitly (Michaels & O'Connor, 1990). For example, we may end a discussion by reflecting on ways in which we had a good (or not so good) scientific argument. Alternatively, we may list ways in which our work today has been like Mary Seeley's work or Dorothy Hodgkin's or Jean van Helmont's. When we encounter a scientist (in books, video, or in person), we reflect on our list of important characteristics of scientists work: Does this scientist exemplify all these traits? Now in class discussions and interviews at the end of the year, I notice students referring to scientists by name: Jean van Helmont, Mary Seeley, Lori Kurth, the Leakeys, Dorothy Hodgkin, John Horner, Elaine Oren. Some of these scientists are giants in the world of science, others are people I know who are willing to share some time with my students. I am intrigued with the ways in which students come to relate to individual scientists and use them as referrants for particular theories or particular ways of being a scientist.

As I interview students at the end of the year now, I am much more excited about the ways in which they describe science and their relationship to science. They seem much less in awe of scientists as being all-knowing, distant from their experience, unapproachable. Scientists are becoming more human to them, and their views of science are richer than Brenda's while they still have a solid understanding of some of the big ideas that Brenda understood so well. I still see room for improvement and change, but these kinds of descriptions of scientific ways of knowing are a giant step ahead of the descriptions I got from Brenda and her classmates:

KR: What else can you tell me about what scientists do?

Nathan: They have to research stuff.

KR: OK, tell me how they research stuff?

N: They have to look at different scientists' perspectives and see what they think, and then they try and see if they thought it was any different. And then they maybe could try and find that other scientist and talk about it, and see if he thought it was a good idea.

KR: Tell about this, "they look at different scientists' perspectives"?

N: Well, if they were in a book and stuff they might read it, and get some ideas and they might say, "Well, I don't think this is right" and try and change their idea.

****

KR: Do scientists travel around for other reasons?

Matt: Yeah, like for meetings with other scientists to share their perspectives and to like collaborate to mix what they have with some others to form some better evidence . . .

I: And what about talking that they do?

M: They talk with other scientists to mix their ideas, collaborate to see if they can solve the problem. A lot of scientists don't just work by theirselves, they collaborate with other scientists and come up with better ideas.

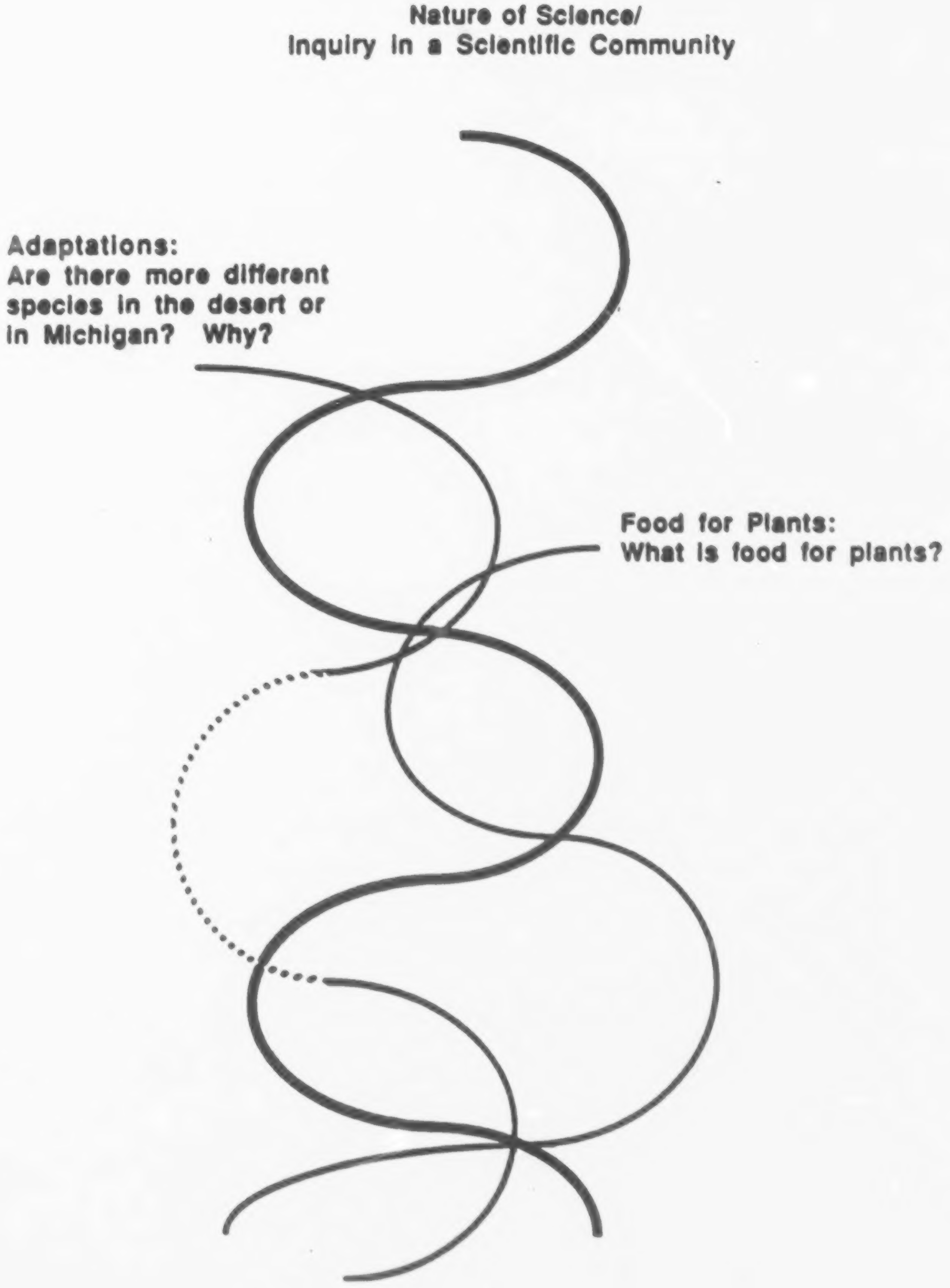
Nature of Science/
Inquiry in a Scientific Community
Adaptations:
Are there more different species in the desert or in Michigan? Why?
Food for Plants:
What is food for plants?

Figure 8. Curriculum strands, Fall 1990.

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I: Do you think it would be easy or hard for scientists to study about humans who lived a million years ago?

Nan: It would be hard because they got to find a lot of evidence, and they got to find a lot of things . . . because there is no proof. [To find out if early humans got married in churches] they'd have to go all around the world and try and find like if they find a church or something, they are not going to say that that is a church where early humans go to get married. They aint going to know.

****

KR: Why is it important to do science?

Michelle: You can find out different things and aren't going with just one point of view like when we did the bean plant, we weren't just looking at the book.

KR: Why is it important not to go with just one point of view?

M: 'Cause you'd be getting your own ideas too, like when we were reading books on plants, we weren't just going by that perspective, we were going by our perspectives, too, like doing different experiments with beans.

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KR: What does it mean to do a science job?

Justin: Scientists explore, are fascinated, they wonder, they don't always have answers to questions.

KR: What is science all about?

J: Science is a lot of learning and fascinating and wondering.

****

KR: Have your ideas about scientists changed?

Heidi: Yes! When I first started science, I used all the stereotypes and now I've learned that they can do anything they want. They can ride a moped, wear grubby clothes. Some work in labs but most of 'em are studying things, finding out things, trying to figure out things.

KR: Were there times in science class when you felt like a scientist?

H: When we did the bean experiments. We were finding the things out, we were the ones that were making the experiments. Some people would like stay in for recess and make up their own experiments.

KR: What kinds of talking do scientists do?

H: They have arguments sometimes, they sometimes talk to each other at meetings about what they found out and how they got that information.

KR: Can you say more about arguments?

H: Well, some people might believe in one thing and some might believe in the other, like if I said the seeds could grow in the dark, other people might say they can't grow in the dark cause they don't have any sunlight and that's part of food, so you'd do an experiment and find out. They can argue about which one they think is right and then they can try or find out which one is right.

KR: Is it a good thing or a bad thing to have arguments in science?

H: I think it's a good thing cause then you learn more about what the other people think and if you're wrong you learn from yourself and sometimes you learn from the other people.

****

KR: Who's good in science in your class?

Nathan: Well all of them are really good cause they contribute ideas and they answer each other's questions and some people might not think it's not very good, but some might think it's a really really good idea. Most of 'em would answer questions and they'd go along with each others' ideas.

I: Were there things I said or did that showed you how to have a scientific discussion?

N: When like Rachel had that idea about how hair might help some stuff grow, and you go "How would hair get into a plant?" and she goes, "I don't know maybe it just fertilizes it." And everybody gets going right after that and they start asking her different questions.

****

KR: What kind so people become scientists?

Tiffany: Before we studied this, or after?

KR: Both.

T: Before I thought it was men, because there's this cartoon--a mad scientist--and he's an old man and he has weird hair. And now I think it could probably be anybody. It could be a man or a woman or anybody, really.

KR: Does this writing in your journal show anything about you as a scientist?

T: That I've used other people's ideas to help change mine and make them better or make them right or sometimes just to improve them.

KR: What things helped you understand in science?

T: Scientific arguments helped because you could change your ideas. People helped you see it different and then it might be better. Experiments help and experiments on our own helped, too. I got to do the experiments I wanted, so I

> could see, I could do an experiment on what questions I had. Like I did one to see where sugar was at because at first I didn't understand that the cotyledon made sugar so then when I did that one, I found out what it was, like the cotyledon was all sugar except the brown part.

****

Tiffany: Scientists do experiments to find answers to questions.

Nan: That's what we did!

T: They have discussions with other scientists about what they think and then they add to their ideas.

Nan: That's what we did!

T: Different scientists can do different experiences and add to their evidence.

Nan: We found evidence too just like scientists. Because we are scientists!

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Learning From Colleagues

After teaching Brenda's class, I moved to a new school and new relationships with school and university colleagues that provided a wonderful setting to pursue more explicit teaching of ways of knowing and being in scientific communities. I wanted to figure out ways to help students develop richer understandings of scientific habits of mind while continuing to help students develop the kinds of connected and useful understandings of science that Brenda had developed.

This setting was a collaborative venture in which Michigan State University and a local elementary school developed a partnership, creating a professional development school in which teachers and researchers would work together to study, to inquire, to develop and test out innovative teaching strategies, to support prospective teachers, and to develop new roles and relationships for teachers, teacher educators, and researchers. As part of this collaborative effort, I participated with three elementary teachers, three doctoral students, and a literacy researcher in a project called the Literacy in Science and Social Studies Project. In the context of this project I again taught fifth-grade science and studied my own practice, exploring learning from teaching in a teacher-researcher role. But there was an important difference. Instead of studying my practice on my own, I had colleagues who were collaborating with me. In various configurations over the last three years, we have supported each others' inquiries through participation in a weekly study group, through co-teaching in elementary and teacher education classrooms, and through co-researching in our classrooms. During 1990-91, for example, I taught science in Barbara Lindquist's classroom while she and Constanza Hazelwood took on researcher roles in the classroom. Planning was a group effort that included Barbara, Constanza, and myself along with Kathleen Peasley (a doctoral student in science education) and Elaine Hoekwater (fifth grade teacher) who were teaching science in the fifth-grade classroom next door and conducting an inquiry into their students' learning. Other project members and teacher education students joined in the inquiry through visits to the classroom, participation in interviews with students in our classroom, and joint study of data in study group sessions and through teacher education classes/independent studies. In contrast with my solo venture into the teacher/researcher role in 1988-89, this was a collaborative model of the teacher/researcher.

This collaborative study of my teaching practice opened my eyes to new ways of thinking about what it means to know in science and about how to represent science in the classroom context. In this work I continued to learn from my elementary students but found myself also learning about science through interactions with elementary teachers, science education colleagues, prospective teachers, and colleagues with interests and expertise in literacy and social studies. These interactions have been particularly helpful in challenging my thinking about the sociological aspects of science and how to represent those in my science teaching. Below I describe three examples of how these interactions have challenged my thinking about what it means to understand science.

Learning about the classroom learning community from a teacher and from colleagues in the LISSS study group. When I began teaching science to the fifth graders in Barb Lindquist's classroom, I was aware of two central goals: (1) to help each student undergo significant and personally satisfying changes in their understanding of a few important concepts in science and (2) to make more explicit to students ways in which the norms developed in our classroom are similar to norms in scientific communities. As Barb watched me teach and especially as she watched the students, she kept saying to me that something important was going on in this classroom that was missing from my formal descriptions of the conceptual change model of instruction I was using and from my descriptions of the kinds of understandings I wanted students to develop. Barb persisted in exploring this issue and was able to articulate it clearly to our LISSS study group as she linked it to an article she had read in which Hermine Marshall (1990) uses a learning versus work metaphor to contrast two types of classrooms.

As we discussed the issues Barb raised in the study group, we came to understand that a key feature of my teaching that made students feel welcome and safe in the "neighborhood of science" was the qualities of the learning community. While it was important that I was starting with students' ideas and by presenting a central question that I hoped would engage them, what was equally important (or perhaps even more important) was the quality of my interactions with students about their ideas. I remember Barb commenting several times something like, "the students believe that you are genuinely involved in the inquiry with them." As we explored these issues further, we defined the qualities of the learning community that seemed to be both different from traditional classrooms (our own classrooms in the past!) and key features that invited even shy, hesitant, and "unsuccessful" students into the inquiry. Some of our ideas about important qualities of science learning communities are represented in Figure 9 and Table 2.

Learning about the relationships between the science learning community and scientific communities from a prospective teacher. After completing her high school biology student teaching, a prospective teacher whom I had been working with in my teacher education role visited my classroom. Elaine Oren was interested in using her observations in my classroom to rethink some of her frustrations during her student teaching--especially the cookbook approach to laboratory work that she had wanted to change into more genuine inquiry. She watched and participated in our class and began talking with me about a variety of questions and issues. Elaine brought a new lens to bear on my classroom. Before returning to school to get her teaching certificate, Elaine had used her biology degree to work as a research assistant in a laboratory on campus. She drew from these experiences in the scientific community to look at the interactions in my classroom. This lens enabled her to raise a question that was very provocative for me: Isn't the learning community you are creating a very idealistic one that misrepresents what real scientific communities are like?

She observed that the science learning community I was creating in the classroom was in some ways "idealistic." In the classroom she observed all ideas being valued and treated with care, a valuing of cooperation and consensus building with a deemphasis on competition and evaluation by grades. She saw human caring and connectedness. In contrast, she observed that scientific communities are not always so cooperative, caring, and polite. Scientific arguments in the real world are often more combative in nature, with scientists valuing assertiveness, ownership of the best ideas, and winning as more important than sharing and caring. Competition for ownership of discoveries can be fierce and lead to a lack of collaborative work. Scientists sometimes value personal toughness over caring: You need to learn how to stand up and assert your ideas and defend them despite strong attacks.

Graduate students in science are often taught to stand on their own two feet and to knock down every challenge to their ideas--to win the argument. There is an attitude that the individual stands alone with challenges like darts that will knock you down (or out of science) if you don't fight them off successfully. And women graduate students more often than men find this mode of discourse difficult and foreign. They also leave graduate school at a higher rate than do men. How do I justify creating my idealistic scientific community in the classroom when the real world of science is often so different? Am I setting kids up for disillusionment and frustration by pretending that science is such an intellectually, socially, and emotionally safe place to be?

I had no immediate responses to Elaine's issues and questions. But fortunately, I found opportunities to pursue these issues with colleagues in a variety of settings. These interactions are helping me think about when, how, and why I might want to help students learn to critique the scientific enterprise--seeing it in all its strengths and weaknesses. Is learning to critique science a key part of knowing and understanding science? Can I help students learn how to engage in rigorous scientific argument which is also cooperative and supportive? Might such teaching provide students with tools that would help them imagine multiple ways of engaging meaningfully and effectively in scientific debate and that would challenge the stereotype that rigorous scientific debate has to be combative and competitive in nature? Might students with such tools be able to broaden modes of discourse in scientific communities in ways that will enrich this scientific enterprise? Through my recent interactions with doctoral students, fifth graders, and school and university colleagues, criticizing science and imagining new ways of doing science has certainly become an important part of my understanding of science.

Learning about sociological perspectives from a doctoral student and fifth graders. Through interactions with Constanza Hazelwood, a doctoral student in science education and a native of Colombia, South America, I began to rethink my understandings of science through sociological lenses. Her research in my fifth-grade classroom focused on race, class, and gender issues and the roles they might play in students' science learning. Constanza studied closely small-group interactions in my classroom, and she frequently interviewed target students about social context issues. Constanza's research at first seemed separate from mine: I thought each of us was investigating different kinds of learning, science learning and social learning. As our collaboration proceeded, I realized how closely the social learning and the science learning were intertwined.

For example, Constanza helped me study and understand differences in communication patterns among girls and boys in my classroom (Hazelwood & Roth, 1992). Her analysis of small-group interactions helped me see how discussions that at one level appeared very productive to me as the science teacher (the group came up with some fascinating questions, explanations, or evidence) may have at another level silenced the girls and other traditional outsiders to science. Constanza noted a pattern of discourse in which the girls had less voice and salience despite holding valuable insights and understandings about the content. If I treated the boys and the girls the same, this pattern would continue, and it might contribute to girls learning that they are not good at science or that science is about being loud and fast in getting your ideas on the table, or about taking the credit for ideas that others came up with.

And then there was Laticia. Only after reading Constanza's paper about this student ("Gender in Black and White," Hazelwood, 1991) was I able to see the special challenges Laticia faced in joining our science classroom not only as a new student in October but also as the only African-American student in the class. If from the beginning I had recognized and empathized with the feelings of Laticia (captured in Constanza's paper) as she negotiated her role as a new student in an all-white classroom, I could have better understood the conflicts and pains she encountered--pains that were different from experiences of new white students in this classroom, pains that would affect her willingness to share ideas in science class.

I look back and regret that I did not have these insights when Laticia entered our classroom. I treated her "just like everyone else" when I now believe it would have been more equitable to give her some special kinds of support. When she joined our class, I tried hard not to notice that she was "different." But looking back in light of the findings from Constanza's observations and interviews with Laticia, I see the special challenges that Laticia faced in sharing her science ideas both in the small-group and in the large-group settings. And I should have been prepared to give her special support. For example, I could have done more to tap her knowledge and experience. In fact, it was some special support that eventually enabled me to connect with Laticia and bring her into our science learning community--but that support came only in a time of crisis when Laticia lost her temper as a result of the isolation and hostility she felt from the girls in her group. After that incident, I looked for ways to help her knowledge and expertise be valued by the group and to help her learn how to communicate in ways that would be accepted by her peers. By strengthening her ability to use scientific discourse effectively, I found a way to highlight her contributions to our science learning community. She succeeded in working effectively with her peers in this context by using rules of scientific discourse that were explicitly taught and shared by all.

Constanza shared not only her analyses of my classroom; she also shared questions about the nature of science and how it should be represented in classrooms. She also brought new bodies of literature to my attention. As she watched students interact in my classroom, she was captivated by new ways of representing science knowledge and new ways of sharing attitudes, values, and ideas about how knowledge is constructed. She recognized a distinct difference in the approach to knowledge in this classroom than in her own previous teaching, and it stimulated her thinking about philosophy of science and science itself. She brought to our study group and later to our Women in Science Education Group new questions about science: What might science become? How might it become a discipline that would be more inviting to females and other traditional outsiders? Like Elaine Oren, she wondered about these students' learning about science as a cooperative, nonthreatening venture in which everyone's ideas are valued. Would their enthusiasm for science be destroyed when they discovered the "real" world of science to be more competitive, elitist, hierarchical? Instead of focusing on changing girls and other science outsiders to make them more "fit" for participation in science, how might science itself change to include a broader representation of alternative perspectives and to become more inviting to those who have traditionally been excluded?

You can see that this question was coming to my attention from multiple perspectives--from Elaine's questions and from Constanza's observations. The question also arose from my interactions with the social studies issues that our LISSS study group in the professional development school explored together.

Continued learning about sociological perspectives from social studies colleagues and fifth-grade students. Elaine Hoekwater and Corinna Hasbach were co-teaching and co-researching in the two fifth-grade social studies classes. They created an American history curriculum that not only involved students in understanding key events in our country's history but that also involved students in critiquing how history is constructed. Students learned to be critical readers of multiple kinds of texts, continually asking questions like: Whose perspective is being represented here? Whose perspective is missing? What different impressions do we get of these events from different sources? Who is writing history? Why might this person tell the story in this way? What evidence is the historian using to construct his/her interpretation? How is language being used to describe events? Would that language seem appropriate from a woman's perspective? an African-American's perspective? a Native-American's perspective? and so forth.

I was impressed with their efforts as I saw fifth graders get involved in these issues in significant ways. I was surprised at the teachers' willingness to dig into such controversial, "adult" issues with young students. And I was struck by the powerful learning tools that students were taking away from this approach to the study of American history. While they will leave fifth grade having encountered fewer episodes in American history (the teachers did not cover the entire chronology of American history from "discovery" until today), they will leave with powerful tools for analyzing history, both history of the past and history-in-the-making. I imagine them as adults reading the newspaper or watching a television program and asking: From whose perspective is this story being told? What evidence are they using to construct their interpretation?

At first, I just found these experiences with the social studies members of our group to be interesting but not related to science. But after Elaine and Corinna's study of Maria-Yolanda, a student whom they taught in social studies class and whom I taught in science class, I realized that the issues and approaches they were taking to a study of history might also have a place in thinking about the construction of knowledge in science.

Elaine and Corinna's teaching and research made Maria-Yolanda visible to me as a Mexican-American student for whom race and discrimination were very salient issues. As with Laticia, I did not genuinely acknowledge Maria-Yolanda as a student of difference. Like the fifth graders in the class, I guess in some ways I just saw her as a student with "a tan that doesn't go away" (Roth, Ligett, Derksen, et al., 1992, p. 30). If I had been more sensitive to the possibilities that her racial difference might be important to her, perhaps she would not have remained such an invisible student in my classroom. Constanza's (I) interview with Maria-Yolanda (MY) at the end of the year was a critical incident for me.

Maria-Yolanda was extremely quiet in science class, and when she did speak to me privately or in her journal I had not been impressed with the quality of her thinking. Her other teachers commented on a similar lack of engagement in academic learning. I remember when Elaine and Corinna chose her to be one of the students interviewed in social studies that I was glad I was not interviewing her for science, because I thought she would have little to say. And yet as I watched the videotape of social studies interviews with her, she was heartbreakingly articulate in talking about her racial experiences and her understandings of social studies concepts about discrimination and invisibility in history. In the following excerpts from her interviews Maria-Yolanda reports her personal experiences with discrimination and then connects discrimination to invisibility, saying that race has a lot to do with why certain groups are invisible in history:

I: Do you see other social conflicts at school besides the boy and girl conflict?

MY: Not really. Well, name calling. Like that's a social conflict because that's not right. There's two people arguing or more.

I: Can you give me an example?

MY: I got one. You know when you came in to talk about Texas and how you grew up? Well, Gary had said, "Well you are just Mexican burritos" and then Ms. Hasbach stopped him and started talking about it. I turned around and I said, "That's not right Gary" and then see we were going back and forth and then Ms. Hasbach said "wait a minute. I just heard something that I didn't like." So that was something that was a social conflict.

I: How did you feel about Ms. Hasbach saying something?

MY: Well I felt good because not every teacher will stop and say something if somebody had started discriminating against you because of your race. (Hasbach, Hazelwood, Hoekwater, Roth, & Michell, 1992, p. 20)

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I: Some groups have been invisible in history. First, let's think about the word invisible. What does that mean?

M-Y: They weren't like nobody really paid attention to them. They discriminated against them and I know the groups. The colored, the Hispanics, and the Mexican American. Those people were very invisible because they didn't have their rights and they were discriminated against. (p. 50)

Despite Maria-Yolanda's own invisibility in the social studies and science classrooms (she rarely spoke in group discussions, for example), she boldly proposes in this interview that she could share her special understandings of racism by making a speech to the whole school about discrimination:

MY: I would understand how the Mexican Americans and the Hispanics used to feel. This is something I think, I don't think a lot of people in there cared because they don't know what it feels like to be Hispanic and discriminated against. And they don't even know what color people [people of color] feel like. I don't think they really cared. I don't think a lot of white people got discriminated against besides the women. (p. 21)

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MY: I would say something [to the school] like people are out there discriminating against people's race because they're different than you but nobody is different because they all have the same feelings. Just because their pigment is different there's nothing wrong with them, they're still human. (p. 21)

But Maria-Yolanda's comments about the journal writing in social studies and about the power of language were the most poignant for me. They helped me identify the opportunities I had missed in helping Maria-Yolanda find science meaningful:

MY: They [the social studies teachers] have those journals, so we could write how we feel. She told us these journals are for how you feel and I've wrote in it a couple times about how I feel about being called a Mexican burrito. (p. 21)

At the beginning of the year in science, Maria-Yolanda had attempted to use her science journal to interact with me in a personal way that went beyond what was required of the class. She privately showed me how she had written in her journal about experiences at home, and she was clearly taking seriously the idea that the journal could be a dialogue with the teacher. At the time, I was impressed with this effort but I did not perceive it as a critical moment in my relationship with Maria-Yolanda. After all, the writing she had done had very little to do with science. It seemed like a nice *personal* moment of connection between Maria-Yolanda and myself, but I did not see it as a way to help Maria-Yolanda connect with *science*. Now as I look back on her consistent silence and disconnection in science class, I realize that I should have encouraged this unintended use of the science journal.

By being responsive to nonscience content in the journal, I may have been able to find ways to help Maria-Yolanda connect the issues that were important to her to our work in science class. But I didn't know until the year was over about Maria-Yolanda's experiences with discrimination and her passionate feelings about this discrimination. A more open-ended journal dialogue with her could have helped me know about her concerns and might have enabled me to find ways to connect our discussions about scientific inquiry and about species and the history of life on earth with her concerns about human interactions and racism. Perhaps her interests could have challenged me to pursue further and more deeply the idea of stereotypes of scientists that I had introduced. Perhaps I could have opened up a critical examination of the way science has been constructed historically and pointed out issues of invisibility in science, ideas that may have challenged students like Maria-Yolanda to make themselves more visible in science.

As I noticed and started to understand more deeply the multiple kinds of differences that my students experienced, I began to see ways that I might be able to support the girls and the boys, the students of color and the white students in ways that were different but perhaps more equitable. Treating them differently to help them learn how to communicate effectively with each other was not treating them equally, but I felt was a more equitable instructional decision. I wanted to help girls, for example, learn how to gain and hold the floor in a conversation.

I have the same kinds of regrets and hopes for students like Maria-Yolanda and Laticia. Their stories have pushed me to rethink what it means to be a member of the scientific community. These students and the social studies members of our group have challenged me to read anew the history of science and to view science as a social construction whose norms, values, and processes are not immutable and inevitable. Our current definition of science was constructed by a limited subset of humans, primarily white Western males. How might the definition of science become broader and richer if it is redefined by humans bringing different experiences, perspectives, voices, histories, and ideas about ways of understanding our world? How can traditional outsiders to science not merely become "members of the club" by adopting white, Western, male behaviors and values but actually change the nature of scientific inquiry in ways that would benefit us all? How can science teachers encourage and prepare all students to not only understand and appreciate science concepts but also to understand the scientific enterprise--to appreciate and value its power to enrich our lives and to critique its unquestioned assumptions and its ways of silencing voices of outsiders? Might a more human and critical study of science--and all its uncertainties--resonate with students who have traditionally felt excluded and alienated from science?

More learning about sociological perspectives in the Women in Science Education Group. These are the kinds of questions that I am now asking about science, about science teaching, and about the students in our science classrooms. I can no longer look at the outsiders in my classroom as "just the same" as everyone else. They bring special histories and experiences that may mean they need different kinds of support in learning science. I recognize the danger here of being perceived as advocating a less challenging curriculum for some students or advocating individualized curricula. In fact, I am arguing that all students can benefit from a much more challenging and perhaps controversial science curriculum than they currently experience and that all students can learn to understand science in much deeper ways that we currently expect from them. I hold high standards for all my students' learning, but I believe that their differing starting places demand different kinds of support in meeting the demands of "really" understanding science (Gardner, 1991). I also recognize the danger of using knowledge about students' starting places to put labels on them that often serve to trap them in the starting gates. I need to explore ways of clarifying my new position and communicating this position to others so I clearly send that message that all students are capable of understanding science in meaningful and complex ways, but that it will take very careful planning and teaching to find ways to help all different kinds of students connect with and develop personally meaningful scientific ways of knowing to launch them out of their personal starting gates and into genuine pursuit of understanding in science.

Currently I am exploring these issues in the context of a study group with female science education doctoral students. The group initially formed in Spring 1992 as an independent study group who wanted to examine together feminist perspectives in science and science education. We met weekly late on Friday afternoons at my home and followed our 2-hour discussions with dinner and continued conversation. This year the group continues to meet every other Friday but there is no longer any formal course credit driving our interactions; we simply recognize the power of this group to stimulate, challenge, and support each other in wrestling with questions about how to change science to make it more hospitable to diverse perspectives and how to represent science to our elementary-, secondary-, and college-level students. We share and discuss articles including our own writing. We link our readings to our experiences in teacher education, K-12 science teaching, scientific research, college-level science teaching, parenting. We help each other think through problems faced in our teaching, research, writing, professional interactions.

One of our group members, Lynne Cavazos, moved to California last summer. In her dissertation study, she is creating and studying how a similar conversation group (in her group there is an emphasis on storytelling and learning from stories) that consists of women high school science teachers might lead to important understandings about how science might best be represented to help girls find science a comfortable and stimulating place for themselves. Our group is following her progress with great interest, for we are interested in figuring out ways to engage a wider range of educators in discussions like ours. We are aware that while all of us are teachers, we are not currently full-time K-12 teachers. Our teaching is meshed with our experiences in research and doctoral level study at the university. In that sense our experiences are very different from the kinds of professional development opportunities available to full-time K-12 teachers.

Our study opportunities are ongoing and in-depth, while we hear from our full-time teacher colleagues that their inservice opportunities are usually "one-shot" deals that are designed to "train" them to use some new methodology. Teachers' professional interactions in other settings (staff meetings, curriculum committees), are also focused on immediate concerns and quick actions. Our group has the luxury of dealing with more complex issues, and we do not leave any particular meeting thinking that now we have it all figured out. Our meetings help us think about actions we might take as teachers, but we are patient with ourselves. We know that we are struggling with difficult issues and that quick answers and actions might be just as detrimental to our students as no action. We provide ongoing support for each other as we try different pathways into these issues with our students; it is interesting how the Friday meeting time (usually a terrible time to get people to attend meetings), which was initially created because it was the only time we could all get together, has become a positive thing for us. We look forward to ending the week with the sharing, stimulation, support , and socializing of this very comfortable group. We wonder: Could a group like ours function in a school setting?

Learning about historical perspectives in science from a history education colleague. Just when I thought I had as many issues on my plate as I could handle, I was challenged by colleagues to take a more serious look at the role that historical perspectives might play in my understanding of science and in my teaching of science. Last summer I had a call from Randy Schankat, a Minnesota educator who had found my articles to be relevant to his work first as a special education advocate and currently as a leader in the quality management arena. He had been reading some of my work and also some by Sam Wineburg, an associate professor at the University of Washington. Sam's expertise is in the areas of learning theory and history education. Randy had this great idea that Sam and I should work with Randy and Jean Ehlinger to create a 2-day workshop that would challenge teachers and curriculum leaders to explore and reconsider "ways of knowing" and "essential learnings." He felt that the disciplinary perspectives that Sam and I could bring would help educators rethink the big goals that should be behind the active outcomes-based education reform effort in Minnesota. He wanted Sam and me to plan a 2-day workshop that would involve participants in reexamining their own learning in history and science and that might also introduce them to new ways of thinking about integration of subject matter areas.

In the course of planning this workshop (mostly over the telephone), I found myself becoming an historian as I learned from this new long-distance colleague. I found myself in new sections of the library looking for primary documents from Antoine Lavoisier's life and searching for Barbara McClintock's acceptance speech for the Nobel Prize (or did she give one?). I was reading and analyzing Laurel Thatcher Ulrich's Pulitzer Prize-winning history, A Midwife's Tale (Ulrich, 1990), in which she provides new insights into New England life in the late 18th century through her study of a midwife and healer named Martha Ballard who kept a daily diary that recorded her work between 1785 and 1812. In the process of exploring these sources, I found myself intrigued with the need to reexamine the history of science. I wanted to know more about Antoine Lavoisier's wife who kept his scientific records, did his scientific drawings, and interacted with his scientific colleagues long after his death (at the guillotine in revolutionary France). And yet in account after account of his life, she was just mentioned. The most detailed accounts given about her focused on her efforts to plead for his life. To what extent was she a contributor to his developing ideas? Did she play a key role in talking with him about his ideas? Or was she more like a secretary? I also wanted to know more about how medicine became more scientific: How did the new physicians who began replacing midwives toward the end of Martha Ballard's life view the knowledge held by midwives? In their training, did they have access to midwives' knowledge or only the formal "scientific" knowledge being generated at the time? What makes knowledge scientific? Who decides? I started realizing that people like Lavoisier in the 18th and 19th centuries were shaping what counts as scientific ways of knowing. Had Martha Ballard's knowledge been tapped and valued, it might have made important contributions both to medical knowledge and practice but also to how science is defined.

I became especially intrigued with this question as I explored Barbara McClintock's life through reading Keller's A Feeling for the Organism (1983). McClintock, a Noble Prize winner for her unconventional and long-deprecated approach to the study of genetics, reminded me of Martha Ballard. Like Ballard, she was deeply connected with her subject of study (in her case, corn plants). Like Ballard, she looked at the whole organism rather than at particular parts. Like Ballard, she was considered unscientific by the scientific community. And yet McClintock's work eventually convinced her critics of its worth. What if Martha Ballard had succeeded in making such a contribution to the scientific community back in 1800? Would medical science be different today? What was gained and what was lost as medical practice became increasingly scientific in the Western tradition of Lavoisier? Can people like McClintock bring new perspectives and approaches to scientific ways of knowing to science and enrich the enterprise by increasing its diversity of methods and norms?

> That there are valid ways of knowing other than those conventionally espoused by science is a conviction of long standing for McClintock. It derives from a lifetime of experiences that science tells us little about, experiences that she herself could no more set aside than she could discard the anomalous pattern on a single kernel of corn. Perhaps it is this fidelity to her own experience that allows her to be more open than most other scientists about her unconventional beliefs. . . .
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> For years she has maintained an interest in ways of learning other than those used in the West, and she made a particular effort to inform herself about the Tibetan Buddhists [and their ability to regulate body temperature and run for hours on end without sign of fatigue]: "I was so startled by their method of training and by its results that I figured we were limiting ourselves by using what we call the scientific method."
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> But these interests were not popular. "I couldn't tell other people at the time because it was against the "scientific method." . . . We just hadn't touched on this kind of knowledge in our medical physiology, [and it is] very, very different from the knowledge we call the only way." What we label scientific knowledge is "lots of fun. You get lots of correlations, but you don't get the truth. . . . Things are much more marvelous than the scientific method allows us to conceive." (Keller, 1983, pp. 200-201)

These interactions with the history of science impressed on me in a new way, a pat phrase I had heard many times before: Science is socially constructed. It opened my eyes to the idea that our current definition of what counts as scientific knowing may be largely an accident of history. If women had played a larger role in creating science, would it be such a competitive enterprise? Would the reductionist, objective, detached approaches to scientific inquiry have been the only ones that were considered scientific?

It also challenged me to want to know more about the history of science. Was the Western science we know today really created by white males like Lavoisier, or did women actually play a significant (but invisible) role in shaping science? In this regard, I want to pursue my exploration of Madame Lavoisier.

This historical inquiry has challenged me to explore the potential value of historical perspectives in science teaching. I find myself wondering whether richer historical accounts and perspectives (not the ones I have found in the sidebars in science textbooks!) might provide a tool that would help students better understand where scientific knowledge comes from and that scientific knowledge is a social construction, not infallible truth.

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Could rich episodes from the history of science help students think about the human aspects of scientists' lives? Could such an historical approach be alive enough to connect with students and help them understand in deeper ways multiple ways of knowing in science?

Learning from colleagues. In each of these situations described in this section, I found myself learning from colleagues not just about teaching science but about science itself. In the next section I advocate the power of learning from colleagues in the professional lives of teachers. What characteristics of the collegial interactions and what disposition of the learners will enable such interactions to be educative in multiple ways--about teaching, about learning, and about the content and the nature of science itself?

Part 5: Implications For Teacher Education And Professional Development

Learning to Learn From Practice

I did not begin my teaching career with either a rich understanding of what it means to understand science nor a disposition to be reflective and inquiring about my teaching practice. I had a strong background in science content, but a limited and superficial understanding of the nature of science, the conceptual connectedness of science, and the usefulness of science in explaining and predicting. Across my teaching career, however, I have had supports that enabled me to continue to develop my knowledge of science. My development of a reflective, analytical stance towards my teaching was essential to this learning process.

As I compare my learning experiences across time with those of other teachers who have had more traditional supports for ongoing professional learning (inservice workshops, summer courses in a master's program, curriculum committees, textbook selection committees), I am struck by the contrasts between my early approaches to learning about teaching and my more recent approaches to learning from teaching. Like my experience in the first years of my teaching, most teachers do not have access to supports that would help them see teaching as research, teaching as inquiry, teachers as lifelong learning. What kinds of changes occurred in my experiences that enabled me to break out of that mold and to become an active inquirer, a reflective practitioner (Schon, 1983), a lifelong learner? And do these experiences provide insights about the qualities that should characterize both preservice teacher education and ongoing teacher development?

A key to my development was learning to become analytical in multiple ways and about multiple aspects of my teaching practice. What were the areas I learned to become analytical about in my teaching practice? The multiple aspects of my reflection and analysis were not limited to teaching strategies and classroom organization matters. This paper highlighted how I learned to become increasingly analytical about my knowledge of subject matter and what it means to understand science. This is an aspect of teacher knowledge too often taken for granted with the assumption that an undergraduate major in a discipline provides you with sufficient knowledge of subject to teach in either elementary or secondary schools. There is little attention paid in traditional inservice education (usually referred to more appropriately as inservice "training") to supporting teachers' knowledge growth in their subject areas. In science, courses are sometimes created at universities to help science teachers "update" their science knowledge, to learn about recent advances in scientific research. But such courses are not designed to support fundamental shifts in teacher thinking about the nature of science and the ways in which science knowledge is constructed.

Another important aspect of teaching that I learned to be analytical about is learners and learning. Although prospective and practicing teachers I work with often have a difficult time seeing what it is they could examine in their students' learning, I have learned across my career how to look closely at both the strengths and the gaps in my students' learning. I have learned to look at multiple aspects of their thinking--including their thinking about subject matter, their thinking about social interactions in and out of the classroom, and their prior knowledge and experiences related to the subject at hand in their world outside of school--and to make conjectures about how different activities and experiences might engage and influence their thinking. And I see multiple aspects of their thinking within each of these categories. For example, I think about their science learning in terms of its connectedness, its usefulness for a variety of purposes (explaining, predicting, describing, designing, appreciating), and its faithfulness to the norms and patterns of thinking in ideal scientific communities. I think about their learning in terms of their awareness and skill in using writing and talking as tools for learning in science as well as for more creative and communicative purposes both in science and in other subjects. I think of their science learning in terms of their development of dispositions to inquire, to make sense of the world around them, to persist with puzzling problems, to be open to changing their minds in light of new evidence, to be critical and questioning about explanations that are presented to them. I am also concerned about their development of dispositions and knowledge that will enable them to act on their knowledge as caring and thoughtful citizens--citizens who both desire and have confidence in their ability to evaluate various arguments provided by scientists, politicians, and advocacy groups to make decisions about how science knowledge should be used in society . . . citizens who want to be not only informed but involved.

What were the key features of the supports that enabled me to develop across time this analytical stance towards my teaching, my own learning about science, and my students' learning about science? As I review my pedagogical autobiography I find five key features of my work that changed after my first few years of teaching. These new features of my work seemed critical in changing my view of teaching from one that is technical and mastered quickly to my current view of teaching as inquiry and lifelong learning:

1. Learning a researcher role
2. Learning from and during teaching about philosophy, sociology, and history of science
3. Interacting with colleagues in a study format across time
4. Having time in my schedule to devote to reflective work
5. Having a supportive team of learning-focused colleagues in my workplace

Learning a researcher role. In my graduate study I formally studied research approaches and participated as a research assistant in classroom-based research on teaching. Key activities in this research that influenced me later as a teacher were observation and analysis of classroom interactions in terms of teacher intentions and student learning, interviews that probed both teacher and student thinking, analysis of student writing in terms of their meaning and experience versus their ability to give correct answers, and study of theoretical frameworks to consider in analyzing the classroom data. Previously it had never entered my mind that research could have anything central to do with my teaching practice. But once I had learned these skills and used them to uncover insights about classroom teaching and learning, I could not unlearn them in the context of my own teaching. When I returned to teaching, I could not imagine teaching without researching.

Learning from and during teaching about philosophy, sociology, and history of science. I am not sure how helpful it would have been for me to study the philosophy, sociology and history of science prior to my teaching experience. I certainly think such study would have been helpful, but I do not think it would have been sufficient. Such study prior to teaching or even in parallel with a professional education preservice program would not have provided the supports needed to use these understandings to analyze teaching and learning. It was important that learning about these aspects of knowing science occurred concurrently with my teaching experience and my developing knowledge of how to be reflective and analytical about my teaching practice.

Learning with colleagues in a study format across time. The various study group formats in which my knowledge has developed stand in stark contrast with traditional inservice workshops and training programs. In these study groups, participants came together because of interests of joint concern and planned ways to develop together knowledge and understanding about shared issues. Participants were not mandated to participate in the groups, and the participants themselves were considered important sources of knowledge and expertise that could help the group move forward. This stands in contrast with inservice workshops where outside experts are brought in to inform teachers about changes they should make in their curriculum and teaching. In the study group model, the need for changes comes from the participants who develop a much greater ownership of both the problems and the needed changes.

The study group format also differs from traditional inservices because of its more patient and deep view of professional learning. In traditional inservice settings, problems are quickly defined (by outside experts), solutions are proffered (by outside experts), and action by teachers is expected immediately. Although the problems are usually complex, teachers are not encouraged to think about them in complex ways--superficial understandings are expected to be sufficient to change teaching practice in sometimes fundamental ways (e.g., moving from a computational to a conceptual orientation to teaching mathematics). In this setting, teacher learning is not transformative. Teachers are not learning to become analytical about their practice; they are learning to take packaged "answers" and implement them in their classrooms in technical rather than thoughtful ways. In contrast, the study group approach values the power of deep learning and understanding for teachers and the importance of enabling teachers to become thoughtful practitioners who can look at educational problems in complex ways and use knowledge in the best interests of their students' learning. In this model of teacher development, genuine learning is recognized as taking time, commitment, and active involvement of the learner. Teacher learning is not expected to happen overnight, and there is no promise of immediate products or actions.

The study groups that have been most challenging and helpful in my own professional growth have included colleagues who bring different kinds of expertise. In such a format I was challenged to listen and learn from colleagues with different experiences and perspectives. Key activities of such study groups in my experience included joint reading and study of research, shared analysis of teaching and learning in our own classrooms, co-planning, co-teaching, and co-researching in classrooms, and analysis of collaborative efforts to synthesize and present our unfolding understandings to others (through writing or presentations)

Having time in my schedule to devote to reflective work. Although time is always tight in our schedules, it is important that the valuing of reflective work be rewarded in the teaching community. In our work in a professional development school (PDS), we have been experimenting with ways to provide reflective time for practicing teachers through restructured schedules and the hiring of additional professional personnel. For example, many teachers in the building participate in a Wednesday morning study group while co-teachers (usually first-year teachers who completed their professional education at MSU and did field work and student teaching in the PDS context) take responsibility for teaching the children. At the high school and junior high school PDSs in our district, daily teaching schedules on Monday, Tuesday, Thursday, and Friday are lengthened to enable a Wednesday morning professional time for teachers; students come to school two hours later on that day. In Japan, such time for collaborative planning and study is built into the teacher's workload. Perhaps we could create new models of teachers' load assignments that varied from year to year, so that teachers would periodically have a lighter teaching load to enable deeper study and reflection.

Having a supportive team of learning-focused colleagues in my workplace. Another key feature of my learning has been the collaborative nature of that work. In my early years of teaching, I relied on my colleagues primarily for social connections rather than professional connections. In fact, in one school in which I taught I avoided the faculty room at lunch time and planning times because the room was filled with belittling talk about both students and other colleagues. There was a tone of bitterness, complaint, futility. I soon became a teacher who came into my classroom, taught children, and went home to plan--alone. Teaching was a solitary venture; if I had continued in that mode I would never have developed the skills and dispositions I know have to examining my practice. It was absolutely essential that I open up my practice to others and work with others to think about that practice.

The kind of professional development work that was invigorating, productive, and engaging for me could not flourish in isolation or in environments where colleagues were focused on the negative and maintaining (and complaining about) the status quo. In my recent work in a PDS setting, I have found that it is essential to find a group of educators who are committed to developing new kinds of professional relationships and who can set aside past frustrations and complaints and hand-wringing about the school system, parents, administrators, children. Otherwise, our study group has to struggle to maintain its professional, forward-looking focus--fighting against those who would turn it into a forum for airing complaints. This sets a tone that is antithetical to the work of the group. It was important for me to find a group of peers who were diverse in their views while sharing a commitment to study, to inquiry, and to the improvement of teaching and learning. It was of critical importance to me and to my colleagues to have a social group where it was safe to think hard about our profession without being dragged into quarrels outside the scope of our work and without fear of being mocked for taking things too seriously or being overly committed. Our commitment has at times been threatening to others outside the group, because we are taking ownership of problems in schooling instead of laying the blame with others, with the system. Many of our colleagues are satisfied with the status quo despite their many complaints about it. These colleagues cannot be forced to embrace a new kind of professional learning and growth, but it is essential that those who do want to explore such growth are given supports to do so without feeling continually attacked for those commitments.

Creating These Kinds of Supports in the Preparation and Professional Lives' of Teachers

In what ways might some of these kinds of supports that enabled my learning be built into the ways that teachers learn in their preparation programs and in their ongoing learning throughout their professional careers?

Learning a researcher role. Certainly, we cannot expect that all teachers will earn doctorates as a way to develop research expertise (although perhaps that is an option that should more often be encouraged for the classroom teacher). But we can organize teacher preparation programs and inservice professional development opportunities in ways that would support educators in developing skills and dispositions toward inquiry. In the Academic Learning teacher preparation program at MSU, my colleagues and I have built into each course and each field assignment an inquiry orientation. I am currently working with student teachers in a course called Interdisciplinary Inquiry. In this course, we examine multiple teacher roles while exploring in depth the role of teacher as inquirer, researcher.

In discussing the purposes and value of inquiry in my introduction to the course, the prospective teachers pointed out to me that every course in their 2-year professional education sequence had included an emphasis on inquiry. In the first course in the program, for example, prospective teachers had studied learning not only by formal study but also by interviewing and studying two target learners in their mentor teachers' classrooms. In each of their methods courses, unit planning and teaching focused on studying and inquiring into the subject matter and into students' learning. The prospective teachers in my class now see an inquiry study about their student teaching as a natural part of their professional education. However, they still see it as something that is piled on top of their teaching responsibilities, an add-on to the business of teaching. My work with them this semester will be focused on helping them see such inquiry as a central part of teaching, not a nice add-on if you have time.

> By "teacher" I mean someone who engages learners, who seeks to involve each person wholly -- mind, sense of self, sense of humor, range of interests, interactions with other people -- in learning. And, having engaged the learners, she finds her questions to be the same as those that a researcher into the nature of human learning wants to ask, What do you think and why? While the students learn, she learns, too. And it helps if, like Paley (1986), she is curious about her students' thoughts. (Duckworth, 1986, p. 490).

> Every lesson should be for the teacher an inquiry, some further discovery, a quiet form of research. (Britton, 1987, p. 13)

These new teachers will not necessarily persist in developing their inquiry skills once they enter the teaching profession. The profession needs to develop ways of supporting teachers in such ongoing inquiry. And practicing teachers (like myself) who have not been introduced to this teacher role as part of their preparation need support in coming to understand various ways in which they can build such inquiry into their practice. The efforts in professional development schools at MSU and elsewhere are providing models of how teachers can be supported in developing "research" skills and orientations to their work. Collaboratives of teachers across schools can also provide the support for this kind of inquiry. There is a growing group of "teacher-researcher" groups developing across the country. We are aware of and trying to connect with these budding networks in Philadelphia (Philadelphia Teachers' Learning Cooperative, 1984; The Philadelphia Writing Project and Project START as described in Cochran-Smith & Lytle, 1990), Boston (Boston Women's Teachers' Group, 1983), Alaska, and Canada (Among Teachers Community, 1992). In addition, Eleanor Duckworth's moon-watching group (Duckworth, 1991) in Cambridge, Massachusetts, provides an interesting model of ongoing subject matter inquiry in teaching.

Learning from and during teaching about philosophy, sociology, and history of science (or other subject matters). How can teachers learn and continue to learn about their subject matters in ways that push their thinking and the depth and breadth of their knowledge? In undergraduate teacher preparation, I see much value in helping students early on learn to evaluate and analyze their professors' teaching and their own learning. Professional education courses or seminars could be paired with key subject matter courses in the prospective teachers' major area of study. These paired subject matter/education courses could be organized to help prospective teachers think about the ways in which the professor and the text are representing what it means to know and understand this subject matter. The professional education seminar could present alternative models or representations to serve as a contrast and to open up prospective teachers' eyes to multiple ways of approaching the subject matter (including philosophical, historical, and sociological perspectives). For elementary teachers, there would be a focus on one major area of study rather than trying to look critically and deeply at multiple subject matter epistemologies. An alternative model being implemented at Albion College in Michigan involves science department faculty in direct work with prospective teachers, working with prospective teachers and teacher education faculty in supporting planning and analysis of classroom teaching of science.

Teacher preparation programs could also challenge students' understanding of the nature of science (or another discipline) by helping students analyze different curriculum materials and school curricula as enacted in local classrooms in terms of how the nature of science is represented. Formal study of the philosophy, sociology, and history of science could be paired with such classroom-based inquiries.

But some learning about these aspects of science will be most powerful if they are connected to the teachers' teaching experience. How can practicing teachers get support in developing and deepening their knowledge and understanding of science? Some interesting models of science teacher development focus on pairing up teachers and scientists in providing teachers with firsthand access to scientific communities. This kind of relationship can be especially helpful if it is a collaborative group of teacher/scientist pairs who can get together to look across experiences and settings to identify patterns and diversity in what it means to know science. The group would be more thought provoking if it included a variety of scientists, including philosophers and historians of science.

But such programs seem limited to schools with access to universities or other scientific communities. What about teachers without such access? How can schools support learning about subject matter? In our study groups in a professional development school, we have found ourselves often supporting each other in understanding more deeply particular concepts or issues in science (Roth, Hasbach, Hazelwood, et al., 1992). We read not only educational research literature but also books and articles about science and scientists. Our group, for example, got particularly intrigued with different paleontologists and their varying theories and approaches to their work. Group members began reading works by Bakker (1986), Gould (1991), Horner & Gorman (1988), Lessem (1992), and Leakey and Levin (1977). The reading and discussion focused on our own exploration of what it means to be a scientist and on the particular theories of the scientists we studied. The long-term benefit was for our students, who soon came to know some of these scientists in ways that enriched their appreciation and understanding of diverse ways of being a scientist. I think this focus on re-learning our subjects was liberating for each member of our group, but it was also the first time in the teachers' 5-24 years of teaching that they had found themselves engaged in such explorations and study. The group did not have scientists or science professors to interact with on a regular basis, but they came to know scientists and their work in new ways that challenged much of their learning about science as undergraduates.

Interacting with colleagues in a study format across time. In teacher preparation programs at MSU, we have created small cohorts of students who go through a series of connected course and field experiences together across a 2-year period. Such a structure for the program has enabled the prospective teachers to learn how to be colleagues who work together, who inquire together, who study teaching and learning together. These prospective teachers enter the teaching profession with an expectation that teaching will be a collaborative venture that includes study and reflection. However, some of these new teachers quickly lose this orientation when they find themselves in school settings that do not encourage or support such collaborative study. How can schools change to enable colleagues to break out of the isolation of their classrooms and to focus on long-term study together rather than quick-fix inservice learning models?

From my experience I would advocate that schools work to create new cultures and norms where collaboration, study, and lifelong, long-term professional learning is genuinely valued and rewarded. Such cultures cannot be created overnight or without cost.

But schools can begin by offering opportunities for small groups of interested teachers to reconfigure their inservice development. Instead of attending district or school-mandated workshops, a small group could be formed around joint issues of interest that they will pursue together across a year or longer. The teachers could be given the responsibility for planning the ongoing work of this study group, using time that traditionally would be spent in attending inservice programs. The group could be supported in involving outsiders on an occasional or regular basis, drawing from the parent community, the scientific community, the local business community, or a university community.

Having time in my schedule to devote to reflective work. As I suggested above, there are ways in which schools could rethink their schedules and priorities that would enable teachers to have more time for reflective work. Some of these options will cost money, others are ways of reconfiguring without additional cost. The Wednesday morning professional development blocks for teachers and administrators used at a number of Michigan secondary schools provides time in the daily schedule for collaborative and solitary reflective work. Arranging such a schedule change depends on a clear faculty commitment to collaborative, professional development work. When there is faculty support and clear communication with the community, it is possible to get enthusiastic support from the community.

Another model used in the Toledo junior high schools involves district support for support teachers, teachers who teach half-time and work half-time on their own professional development and in the support of the development of their colleagues (Madsen & Lanier, 1992). In the Toledo model, support teachers work in classrooms with other colleagues. In addition, math and science teaching schedules are arranged to enable all the science teachers (and all the math teachers) to have a shared planning hour. This provides a time for collaborative work, although it takes away from individual teachers' private reflective time.

Within the constraints of more typical teaching schedules, we can more creative about the uses of teacher time. In her first year of teaching at Kodaikanal International School in India, Amy Stempel describes a mentoring program in which new teachers each select a subject matter area teacher mentor. In addition to the support of the mentor, the English Department meets once a week, not just to handle administrative functions, but to focus on teaching methods and resources that would support the teaching efforts of the department. In addition, each teacher is observed by someone once a week and each teacher observes someone else once a week. The walls of isolation are broken down as teachers work together to identify problem areas in teaching, to learn together from successes and good ideas, and to develop new ideas together. Stempel points to the benefits of this collaboration with colleagues:

> I can't imagine teaching without them. My worst moments as a new teacher surprisingly were not those times when everything went wrong but those moments when I felt most alone. Tough times are a part of any job, perhaps teaching more than most. But the often solitary nature of teaching can make new teachers feel like a miserable failure when in fact they are simply experiencing growing pains. Without a mentor and a supportive department, I doubt I would consider teaching a career possibility. (Stempel, 1993, p. 6)

Reorganizing time in elementary schools takes more creativity, since elementary students cannot be left home for two hours on Wednesday mornings. Our efforts in professional development schools center around the hiring of regular, part-time professionals we call co-teachers. Because these are typically new teachers and because the work is part-time and year-long contracts only, the costs are less than would be involved in hiring additional regular school personnel. These positions are often attractive to new teachers or to teachers who are temporarily out of the workforce because of parenting demands and priorities. The co-teachers have a regular weekly schedule, working in 1-3 different classrooms. For example, one co-teacher might work in two different first-grade classrooms teaching science four days a week to each class, providing 4 hours of reassigned time for two regular classroom teachers. Perhaps schools can begin to hire co-teachers on a regular basis in lieu of using substitute teachers periodically for inservice professional development activities. Such co-teachers may only be available for one or two teachers each year, but this could provide at least rotating support for additional reflection and study for teachers.

Another option might be to lengthen the school day and to simultaneously decrease teachers' time spent actually teaching children. In China and Japan teachers spend only about 60 percent of their time at school actually in charge of classes. Their school days are typically longer than American school days, but their teaching loads are less. The average teacher in Beijing teaches no more than three hours a day. The rest of the school day is spent preparing and correcting lessons, working with individual children, consulting with other teachers, and so forth. This schedule enables their planning to be much more "polished" and focused (Stigler & Stevenson, 1991).

The point I am trying to make is not that we should copy any of these models, but that we should think creatively about ways that teachers' workload can be shifted so that time for learning and reflection is regularly available. We also need to reconsider this as a priority in our schools and be willing to make some trade-offs and to pay the price to acquire this time for teachers.

Having a supportive team of learning-focused colleagues in my workplace. Not all teachers will eagerly embrace this model of teacher development, and the model will not work if teachers are forced to buy into it. What is important in getting such an approach started is to identify a core group of colleagues (preferably within a building or within a district) who are enthusiastic about such an opportunity and who see such an opportunity as valuable to their teaching and professional lives. These colleagues should self nominate themselves for the creation and participation in long-term study groups, and they should be supported in these efforts with as much time and resources as possible. To give them freedom to pursue this line of work, other teachers should feel like they have genuine choices about other kinds of professional development activities. If the teachers who choose not to participate perceive that the group of teacher inquirers is receiving all the support and resources, the resentment they feel will grow and might contaminate the efforts of the inquiry group(s). Learning-focused colleagues need to be supported in finding each other and need to be protected from becoming objects of jealousy and resentment within the school or district. My hope is that new graduates of teacher education programs will come to the profession looking for this kind of teacher as learner role and for this kind of collegial support. Thus, changing the culture of schools from a technical orientation to an intellectual and inquiry orientation will be supported by teacher education programs.

Concluding Remarks

As I wrote this pedagogical autobiography I often found myself wondering about the usefulness of such a project. Yesterday, as I realized I was nearing completion of this tome, I found myself engaged in a conversation with my 14-year old son about the nature of autobiography. Is a person who writes an autobiographical piece "conceited" and self-absorbed? Why would others want to read about the particulars of my experience? I thought about some of the teachers who had interacted with me in professional development schools who felt that it would be "bragging" to write about their experiences with alternative teaching and assessment strategies, with special programs for "at-risk" children, with productive connections between school and community. Was the writing of this piece simply a personal learning and synthesis activity for one teacher, or is there a wider use for such an autobiography?

As I thought across the kinds of teaching autobiographies (and biographies) that exist in the education literature (Growing Minds, Herbert Kohl, 1984; Lives on the Boundary, Mike Rose, 1989; White Teacher, Vivian Gussin Paley, 1979; Calling: Essays on Teaching in the Mother Tongue, Gail B. Griffin, 1992; Escalante: The Best Teacher in America, Jay Mathews, 1988), I was intrigued by three observations: the popularity of these autobiographies among teachers, the power of these autobiographies of teaching to contribute to our professional knowledge, and the contrasts between these autobiographies and traditional educational research. Yet despite these observations, my experience suggests that such pedagogical autobiographies rarely receive the attention and status of more "systematic" research in education. For example, prospective teachers in teacher preparation programs and practicing teachers in masters' level programs rarely encounter these kinds of books on their course reading lists.

Perhaps the autobiographies are too personal and particular to be of wider interest among professionals. In this regard, research studies promise more generalizability. But is such generalizabilty warranted in a profession that is so governed by particulars-particular learners, particular school contexts, particular teacher strengths and weaknesses?

Autobiography is one way that teachers have begun (albeit in a limited a way) to share the knowledge they are developing from their experience. It is my hope that as teachers come to value and develop as inquirers into their own practice, they will begin to share more about their learning and experience with the professional community - breaking down the walls between classrooms through such communication. I do not think that this sharing of knowledge can be limited to formal research reports. We need a variety of ways in which teachers with valuable knowledge can share that learning. Autobiography is one way; I would like to see more teachers exploring their autobiographies and drawing from them to highlight issues of interest and significance in the teaching profession.

In my case, I hope that my autobiographical tale, while certainly not of the literary quality of those I mentioned above, will provoke thinking about teachers' developing subject matter knowledge, particularly in science. I hope the particulars of my experience and my students' experiences will provide concrete images of ways in which teachers can be supported to become analytical, reflective practitioners whose knowledge of teaching, learning, and subject matter can grow and deepen across a professional career. For intending teachers and experienced teachers who have not examined science closely before, I hope that my story will open up some new avenues in thinking about how they might come to know science in more diverse ways. For those whose knowledge of science is deeper, richer and more diverse than mine, I hope that they might be inspired to communicate about their own understandings of science and the kinds of supports that enabled that knowledge to develop. In that sense, I hope that my autobiographical venture will become intertwined with the biographies of others.

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